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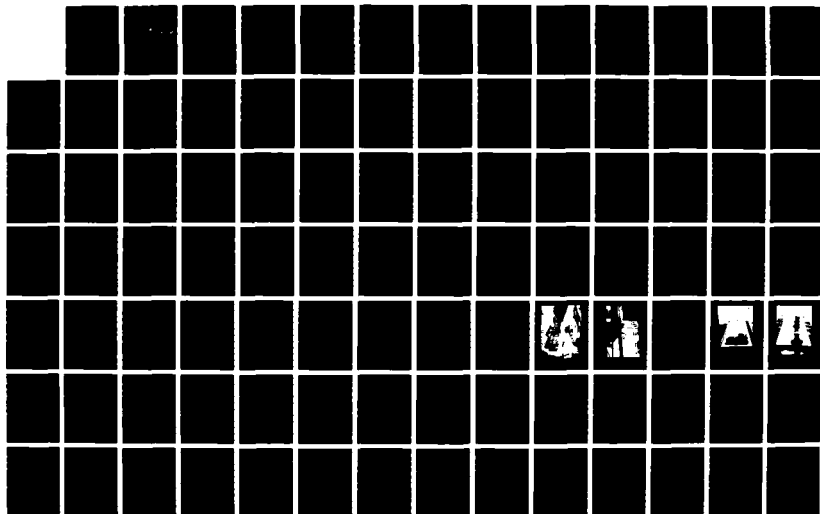
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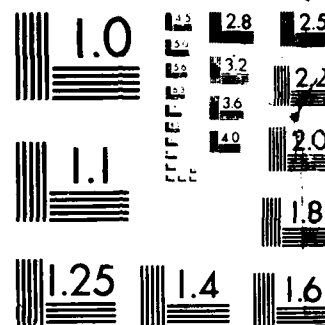
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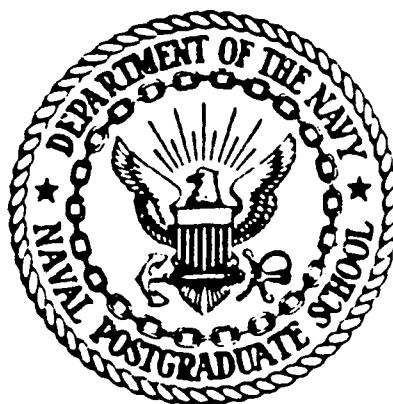


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# THESIS

THE THERMAL BEHAVIOR OF FILM COOLED  
TURBULENT BOUNDARY LAYERS AS  
AFFECTED BY LONGITUDINAL VORTICES

by

Alfredo Ortiz

September 1987

Thesis Advisor:

P. M. Ligrani

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The Thermal Behavior of Film Cooled  
Turbulent Boundary Layers as  
Affected by Longitudinal Vortices

by

Alfredo Ortiz  
Lieutenant, Colombian Navy  
B.S., Escuela Naval "ALMIRANTE PADILLA", 1983

Submitted in partial fulfillment of the  
requirements for the degree of

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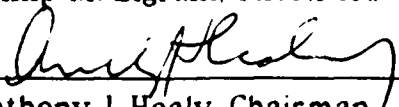
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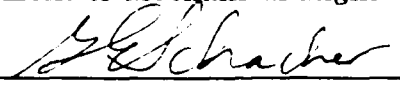
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## ABSTRACT

Heat transfer effects of longitudinal vortices embedded within film-cooled turbulent boundary layers on a flat plate were examined for freestream velocities of 10 m/s and 15 m/s, and for blowing ratios ranging from 0.47 to 1.26. Moderate strength vortices were employed having circulation to freestream velocity ratios of about 1.6 cm. Spatially resolved heat transfer measurements from a constant heat flux surface and mean temperature distributions in spanwise planes show that local heat transfer is significantly affected by spanwise vortex position, and blowing ratio. Of particular significance are boundary layer and vortex structural changes which occur at high blowing ratios. *Keywords:*

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## TABLE OF SYMBOLS

$A$	-	area, $m^2$
$C_d$	-	discharge coefficient
$C_p$	-	specific heat at constant pressure, $J/Kg \text{ } ^\circ K$
$d$	-	injection hole diameter, $m$
$E_{bi}$	-	emissive power, $W/m^2$
$F_{ij}$	-	radiation view factor
$h$	-	heat transfer coefficient (spanwise averaged) as define by, $q''/(T_{r\infty} - T_w)$ , $W/m^2 \text{ } ^\circ K$
$h_f$	-	heat transfer coefficient with film cooling (spanwise averaged) as define by, $q''/(T_{aw} - T_w)$
$j_i$	-	radiosity, $W/m^2$
$K$	-	thermal conductivity, $W/m \text{ } ^\circ C$
$M$	-	blowing rate
$P$	-	static pressure, $Pa$
$R$	-	gas constant
$Re_d$	-	Reynolds number based on the diameter of injection holes
$Re_x$	-	Reynolds number based on the downstream distance from the boundary layer trip.
$St$	-	Stanton number
$St_0$	-	baseline Stanton number, no film cooling, no vortex
$St_f$	-	Stanton number with film cooling only
$T$	-	static temperature, $^\circ K$ , $^\circ C$

- U - mean velocity, m/s
- X - downstream distance as measured from the boundary layer trip, m
- Y - vertical distance from the test surface upward, cm
- Z - spanwise distance from the test section center line, cm
- $\xi$  - unheated starting length (1.10 m)
- $\epsilon$  - radiation emissitivity
- $\eta$  - effectiveness of film cooling
- $\rho$  - density, Kg/m<sup>3</sup>
- $\theta$  - non-dimensional coolant temperature,  $(T_{rc} - T_{r\infty})/(T_w - T_{r\infty})$
- $\delta$  - boundary layer displacement thickness, m
- $\sigma$  - Stefan-Bolzman constant

#### SUBSCRIPTS

- aw - adiabatic wall
- c - coolant at exit of injection holes
- i - isentropic
- o - stagnation condition
- p - in plenum chamber
- r - recovery condition
- w - wall
- $\infty$  - free stream

## I. INTRODUCTION

The increasing need for greater efficiency in gas turbine engines has resulted in higher turbine inlet temperatures. Consequently, combustors and turbine blading are subject to greater amounts of thermal stress, thermal fatigue, and creep. At present, gas turbines such as those associated with military applications, have inlet temperatures as high as 1800-2000 °C, [Ref. 1]. While the development of improved alloys with higher melting points is part of the solution, the development of efficient cooling systems is just as important [Ref. 2]. In order to design an efficient cooling configuration, the heat transfer distributions for the gas turbine components are needed. Because of the complex geometries and flows involved near blades and endwalls, accurate convective heat transfer rates are difficult to obtain. [Ref. 3]

Ongoren, [Ref. 4], described the flow in a turbine cascade. As the inlet boundary layer approaches the blade, just in front of the blade, a horseshoe vortex forms. At the saddle point, it splits into a vortex on the suction side, and a vortex on the pressure side. The pressure side vortex becomes the passage vortex, moving from the leading edge of the blade towards the low pressure side of the adjacent blade. As the suction side vortex convects along the blade, it is eventually pushed away by the passage vortex from the adjacent blade. A smaller, corner vortex rotates in opposite direction to the passage vortex as was verified by Sieverding, [Ref. 5].

The passage vortex is an example of a longitudinal vortex embedded in a film cooled turbulent boundary layer. In most cases, an embedded vortex

has a cross-stream length scale approximately equal to the boundary layer thickness. Therefore, the vortex is capable of strongly perturbing the boundary layer structure and modifying the heat transfer characteristics. In addition, longitudinal vortices usually maintain their coherence over a long streamwise distance, meaning that the heat transfer effects behind an effective vortex generator are likely to be very persistent. [Ref. 6]

Film cooling is used to provide a layer of cool fluid between a surface and high temperature free stream gases to which it is exposed. The film cooling not only acts as a thermal insulator but also as heat sink for the hot freestream gases. The overall effect of the film cooling is to reduce the temperature of the developing boundary layer, which in turn reduces the heat transfer to the surface. In the present study, the heat flux is calculated from :

$$q'' = h(T_w - T_{r\infty}) \quad (\text{eqn. 1.1})$$

where  $h$ , includes the effect of the film cooling for constant wall heat flux,  $q''$ , and constant free stream temperature,  $T_{r\infty}$ . In the present experiment variations of  $h$  correspond to variations of the wall temperature,  $T_w$ . When  $T_w = T_{r\infty}$ , equation 1.1 indicates that  $q'' = 0$ , which may not be the case when film cooling is present.

Goldstein and Chen, [Ref. 2], defined an adiabatic wall effectiveness for film cooling using:

$$\eta = \frac{T_{aw} - T_r}{T_{oc} - T_r} \quad (\text{eqn. 1.2})$$

The heat transfer is then calculated from :

$$q'' = h_f (T_w - T_{aw}) \quad (\text{eqn. 1.3})$$

Here,  $q'' = 0$  when  $T_w = T_{aw}$  with film cooling. Without film cooling  $T_{f\infty} = T_{aw}$ , and equations 1.1 and 1.3 are the same.

Numerous studies have been conducted on the effects of film cooling on heat transfer, effects of secondary flows on heat transfer, and more recently, on effects of film cooling and secondary flows on heat transfer in a turbulent boundary layer. Summarizing the results of experimental research on the effects of secondary flows in turbine blades passages over the past decade, Sieverding (1984) concluded that it is absolutely essential to establish the significance of secondary flows at off design conditions, in particular in regard to leading edge vortices.

Studying the effects of film cooling and secondary flows on heat transfer, Golstein and Chen (1985) performed an experimental study on the influence of the end wall on film cooling of gas turbine blades using a single row of injection holes. Two years later, the same authors performed a similar study but this time employed two rows of injection holes for the film cooling, [Ref 7]. From these two studies, the authors concluded that, in the convex side of the blade there is a triangular region where coolant is swept away from the surface by the passage vortex, while the concave side was not significantly affected by secondary flows originating near the endwall. Other study on film cooling effects is given in [Ref. 8].

Eibeck and Eaton (1987), conducted a study of a longitudinal vortex embedded in a turbulent boundary layer over a constant heat flux plate. The authors found significant increases and decreases in local Stanton numbers, due to the thinning of the boundary layer on the downwash side of the vortex and thickening on the upwash side of the vortex. Spanwise heat transfer variations became larger as the circulation of embedded vortices increased. [Ref. 6]

Investigating the interaction between a single weak streamwise vortex and a two-dimensional turbulent boundary layer, Russel, Pauley and Eaton (1987), observed a rapid growth of the vortex core, and a flattening of the core shape when the dimension of the core radius became comparable to the distance of the vortex center to the surface. Adverse pressure gradient caused an increase in the rate of core growth, and a stronger distortion of the core shape. These authors also provide an extensive review of work on vortices in boundary layers. [Ref 9]

In [Ref. 10], a study was conducted on heat transfer distributions and film cooling effectiveness on the endwall of an airfoil, using a full annular low aspect ratio vane cascade. The authors demonstrated the importance of the horseshoe vortices and secondary flows on the heat transfer and film cooling distributions.

Recently, Joseph (1986), conducted a study of the effects of embedded vortices on heat transfer in film cooled turbulent boundary layers. The author showed that the effects of the vortex on heat transfer are significant and important : on the downwash side of the vortex, heat transfer is augmented, effects of the film cooling are negated and local hot spots will exist.

Near the upwash side of the vortex, coolant is pushed to the side, appearing to augment the protection provided by the film cooling, [Ref. 3]. Evans (1987), studied the fluid mechanics of vortices in boundary layers with film cooling, and showed that the vortices completely dominate the flow field, especially near the downwash side [Ref. 1].

The objective of this thesis is to increase the understanding of the effects on heat transfer, of a longitudinal vortex embedded in a film cooled turbulent boundary layer as affected by : 1) spanwise vortex position relative to the location of film cooling injection holes and, 2) blowing ratio. These effects are important regarding turbine blade and endwall heat transfer. The study was carried out under a series of steps. The first, was the design and construction of the heat transfer test surface, followed by qualification test to verify uniform wall heat flux, and an energy balance to identify and quantify the heat losses. After completion of the experimental apparatus, four types of heat transfer test were conducted : (1) heat transfer data with developing boundary layer only, (2) boundary layer and embedded vortex, (3) boundary layer with film cooling only, and (4) boundary layer with film cooling and embedded vortex.

## II. EXPERIMENTAL APPARATUS

### A. WIND TUNNEL

The wind tunnel pictured in Figure 3., built by Aerolab, was designed to provide a flow field from the nozzle with uniform velocity and low turbulence intensity. It is designated the NPS Shear Layer Research Facility (SLRF).

#### 1. Description.

The SLRF is a wind tunnel of the open circuit blower type with fan upstream and air entering the blower inlet from the surrounding room. The air speed through the test section can be adjusted from 5 to 40 m/s. The tunnel frame has leveling screws to adjust the center line of the tunnel to a horizontal position. The discharge of the fan slips into the inlet of the diffuser with a 1.6 mm clearance to isolate vibrations from the fan to the wind tunnel body. The diffuser section contains a filter pack and a nozzle leading to test section. The test section is a rectangular duct, 3.048 m long and 0.6090 m wide. It is designed with numerous pressure tabs and four 38 x 20.3 cm access ports along each of the side walls to provide easy access. The top wall is a continuous panel fabricated from 4.76 mm thick Lexan sheet, continuously sealed with neoprene along the edges. The ceiling height is adjustable to permit changes in the pressure gradient along the length of the test section. Additionally, the top wall contains numerous instrument ports for the measurements of various flow characteristics. The floor of the test section consists of three 0.6096 m and one 1.2192 m long sections which are



removable and replaceable. These sections are all 0.6090 m wide and are sealed with "O" rings around the sides. Further discussions of the wind tunnel are contained in [Ref. 11] and [Ref. 3: pp. 38].

A schematic of the test section components with the coordinate system employed in the present study are shown in Figure 1. An unheated starting length of 1.10 m exists upstream of the heated test surface. The injection nozzles are located 1.08 m downstream of the boundary layer trip and 0.02 m upstream of the test surface. The leading edges of the vortex generators are placed 0.479 m downstream of the boundary layer trip as shown in Figure 2.

## **2. Qualification and Performance.**

Prior to its relocation, extensive qualification tests of the Shear Layer Research Facility were conducted by Ligrani, [Ref. 12]. Results show that the variation of total pressure at the exit plane of the nozzle is less than 0.4% at 26 m/s and 34 m/s. Mean velocity varies less than 0.7% for the same mean freestream speeds. From five-hole pressure probe measurements, the velocity angle deviation is nowhere greater than 0.6 degrees at the nozzle exit plane.

Profile measurements of the mean velocity and longitudinal turbulence intensity in the turbulent boundary layer developing at 20 m/s indicate normal, spanwise uniform behavior. For this qualification test, and all results which follow, the boundary layer was tripped near the exit of the nozzle with a 1.5 mm high strip of tape. For the present study, total pressure measurements along the test section were made after relocation of the SLRF, in order to adjust the top wall for zero pressure gradient. The

maximum pressure difference along the test section was 0.007 in of  $H_2O$ . Free stream turbulence intensity was measured to be  $0.00085 \pm 8.5$  (one hundredths of one percent or 0.085%) at 20 m/s, increasing to 0.00095 at 30 m/s.

## B. INJECTION SYSTEM.

The injection system provides film coolant at temperatures above ambient. The coolant is ejected from a single row of injection holes into the boundary layer developing along the bottom wall of the test section. The diameters of the injection holes were scaled relative to boundary layer thickness to be similar to a turbine blade, with  $\delta/d$  ratio ranging from 0.37 to 0.40. The free stream air is at ambient temperature, thus the direction of heat transfer is opposite that of a gas turbine. The temperature difference  $T_w - T_{r\infty}$  range for this study has been kept less than 20 °C. to minimize the effects of variable fluid properties.

The injection parameters  $M$  and  $\theta$  were scaled to resemble parameters near gas turbine blades where  $M$  ranges from 0.47 to 1.26 and  $\theta$  varied from 1.39 to 1.69. Since the average temperatures of the coolant, plate and freestream were approximately the same for different runs,  $T_{rc} = 51$  °C, and  $T_w = 40$  °C and  $T_{r\infty} \approx 20$  °C, variation of  $\theta$  was not a parameter considered in this study. Due to the reverse direction of heat transfer for the present experimental apparatus  $T_{rc} : T_{r\infty} : T_w$  ratio is 1.27 : 0.5- 0.55 : 1.0 as compared to 0.67- 0.83 : 1.5 : 1.0 for actual gas turbines.

## 1. Description

Air for the injection system originates in a two stage, 150 psig Ingersoll-Rand air compressor, 10 HP, model # 71TD. From the compressor air flows through an adjustable pressure regulator, a cut-off valve, a reinforce flexible tubing (2.54 cm inside diameter), a moisture separator, a flow regulator, a Fisher and Porter rotometer (full scale  $9.345 \times 10^{-3}$  m<sup>3</sup>/s, 19.5 SCFM, model # 10A3565A), a diffuser, and finally into the injection heat exchanger and plenum chamber. The rotometer monitors the flow rate for film cooling.

A photograph of the chamber, the row of film cooling holes and vortex generator is shown in Figure 3.b. The chamber is constructed of 1.27 cm plexiglass, with outside dimensions of 0.305 x 0.508 x 0.457 m. The internal structure consists of three thin metal plates 0.381 x 0.508 m, starting 5.08 cm from the bottom and proceeding up at 5.08 cm intervals. Two silicon rubber heaters, 0.381 x 0.483 m, 120 volts, are separately placed over the bottom two plates. The heaters are controlled through a Powerstat variable autotransformer, type 136. The top surface contains 13 plexiglass injection tubes 8 cm long each, with an inside diameter of 0.952 cm (3/8 in) with a l/d ratio of 8.42. The 13 injection nozzles are incline at angle of 30°, with a three diameter spanwise spacing between center lines. The middle tube is located on the center line of the test surface.

Three pressure taps, positioned at the center of the front and two side faces of the injection plenum chamber, are used to measure  $P_{oc} - P_{\infty}$ . Three 0.254 mm diameter copper-constantan wire thermocouples with

welded joints are placed at different locations inside the plenum chamber to measure  $T_{op}$ .

## 2. Qualification and Performance.

Extensive qualification of the injection system was conducted by Joseph, [Ref. 3: pp. 23-26]. Results show that the uniformity of the plenum chamber pressure,  $P_{oc}$ , was satisfactory over the range of the injection conditions with differences of about 1% in the spanwise direction and a maximum of 4% occurring for only one case at low flow rate of  $0.327E-4$  m<sup>3</sup>/s. This is equivalent of a blowing ratio  $M$  of 0.004 at  $U_{\infty} = 10$  m/s.

The plenum produces a reservoir of air at an elevated temperature and pressure, which is near stagnation conditions. The temperature at the exits of the injection tubes,  $T_{rc}$ , is different from the temperature of the plenum of the injection chamber,  $T_{op}$ , due to conduction through the tubes surface to the surrounding air. It is more convenient to measure  $T_{op}$ , whereas  $T_{rc}$  is needed to calculate the injection parameters. Thus a relation between  $T_{rc}$  and  $T_{op}$  was needed and found from experiment to be  $T_{oc} = 1.455 T_{op}^{0.865}$ . Because of the low velocities employed, (and negligible viscous dissipation),  $T_{oc} \approx T_{rc}$  within a fraction of a degree.

In order to determine injection parameters, the following quantities must be measured,  $P_{\infty}$ ,  $T_{\infty}$ ,  $V_c$ ,  $P_{oc}$ ,  $T_{oc}$ , and  $A$ , the area normal to the flow of the injection holes, designed to be  $9.2633E-4$  m<sup>2</sup>. The coolant velocity is then given by:

$$U_c = \frac{V_c}{A} \quad \text{(eqn. 2.1)}$$

The static density is estimated using :

$$\rho_c = \frac{P_\infty}{RT_c} \quad (\text{eqn. 2.2})$$

The mass flux,  $m_c$ , is the product of  $U_c$  and  $\rho_c$ . To calculate the isentropic mass flow,  $\rho_{ci}$  and  $U_{ci}$  are found using

$$\rho_{ci} = \frac{P_\infty}{RT_{op}} \quad (\text{eqn. 2.3})$$

and

$$U_{ci} = \sqrt{\frac{2(P_{oc} - P_\infty)}{\rho_{ci}}} \quad (\text{eqn. 2.4})$$

The product of  $\rho_{ci}$  and  $U_{ci}$  for compressible flows may be given as :

$$(r_c U_c)_i = P_\infty \left( \frac{P_\infty}{P_{oc}} \right)^{\frac{2}{\gamma}} \left[ \frac{7}{RT_\infty} \left( 1 - \left( \frac{P_\infty}{P_{oc}} \right)^{\frac{2}{\gamma}} \right) \right] \quad (\text{eqn. 2.5})$$

Discharge coefficients,  $C_d$ , are then estimated using :

$$C_d = \frac{\rho_c U_c}{(\rho_c U_c)_i} \quad (\text{eqn. 2.6})$$

In order to check the injection system, discharge coefficients were measured as volumetric flow rate was changed. Results are given in Figure 4 as a function of Reynolds number for 13 injection hole locations and 7 injection hole locations. Discharge coefficients range between 0.5 and 0.730.

and increase with Reynolds number. For  $Re = 3 \times 10^5$ , discharge coefficients collapse closely around a value of approximately 0.72. Because these results are consistent with those of [Ref. 8], satisfactory injection system performance is indicated.

### C. HEAT TRANSFER SURFACE.

The heat transfer surface was designed and developed to provide a constant heat flux over its area. The average surface temperature may be adjusted and maintained from ambient up to about 60 °C. The plate was constructed so that its upward facing part is adjacent to the wind tunnel air stream, with minimal heat loss by conduction from the sides and beneath the test surface. The plate itself has been instrumented to measure temperatures with thermocouples placed just beneath the foil surface. A film of liquid crystals is sprayed over a layer of black paint painted on the foil.

#### 1. Description.

A photograph of the heat transfer surface is shown in Figure 5.a. The design is based on ones used at the University of Minnesota [Ref. 13] and [Ref. 14], and provides more uniform heat flux and better spatial resolution of temperature than the surface used by Joseph, [Ref. 3: pp. 27-36]. It consists of a thin stainless steel foil, AISI 302 full hard, 0.2032 mm x 1.3 m x 0.467 m, painted flat black with 7 layers of liquid crystals. Attached to the under side of the surface are 126 copper-constantan thermocouples. 120 of these have flattened tips and were manufactured by Marchi associates (type MA 396T-30-96-FEP-FJ), the remaining six have round junctions and were manufactured by Omega Engineering, Inc. Thermocouple lead wires are

located in grooves cut into a triple sheet of 0.254 mm (10 mil) thick double sided tape, manufactured by the 3M Company), as shown in Figure 5.b. The grooves are then filled with RTV. A thin foil constant heat flux heater, 1.0 mm x 1.143 m x 0.457 m, 120 V/1500 W, manufactured by March Associates, is attached to the tape with Electrobond epoxy. Beneath the heater is a 12.7 mm (1/2 in) thick lexan sheet, followed by a 25.4 mm of foam insulation, 82.55 mm thick styrofoam, three sheets of 25.4 mm each lexan and one sheet of 9.53 mm thick balsa wood, as shown in Figure 7.

Around the edges of the foil, grease was inserted between it and the plexiglass frame to fill any small gaps resulting from thermal expansion. In addition, both the upstream edge and the trailing edge were taped to the bottom wall of the test section. Since additional vertical movement of the foil above the bottom wall of the test section occurs due to thermal expansion during heating, the level of the surface is adjustable and maintained level with the test surface by adjusting screws in the plexiglass frame supporting the heat transfer surface from below. During heat transfer tests, the top surface of the foil remained remarkably flat and smooth with minimal surface irregularities. The surface temperature is controlled by adjusting input voltage to the heater using a Standard Electrical Product Co. variac, type 3000B. With this type of heat transfer surface, good resolution of temperature was achieved without hot spots.

Thermocouples are placed on the surface as shown in Figure 6. In each of the six rows, 21 thermocouples are located 1.27 cm apart from each other. The first row of thermocouples is located at 5 cm from the leading edge of the test surface, the second is 10 cm further downstream with

respect to the first, the third is 15 cm apart downstream from the second row, and the rest of the thermocouple rows are 20 cm apart from each other

## **2. Qualification and Performance**

The present test surface was the second one constructed for this experiment. The first one could not be used since it had hot spots located under the thermocouple lead wires where the surrounding liner was not properly attach to the heater. In the second surface, this problem was remedied by increasing the thickness of the liner.

To test the second heat transfer surface, a Huges Probeye Thermal Series 4000 Video System , consisting of a infrared and video camera with display screen, was used. Surface temperatures were measured as the test surface was heated outside the wind tunnel, since the system could not see through wind tunnel walls. With this system temperature variations as small as 1 °C, can be measured. The surface was observed under three operating conditions : natural convection with a surface temperature of approximately 35 °C, forced convection from the leading edge with a surface temperature of about 40 °C, and force convection from the trailing edge, with a surface temperature of about 40 °C. Results showed that most of the heat transfer surface temperatures were spanwise uniform within a fraction of a degree for all three tests. The only exceptions were several small cool spots with temperatures about 1 °C lower than the rest of the plate, located between rows of thermocouple lead wires near the edges of the plate.

A second test using the liquid crystals was performed to further qualify the test surface. The liquid crystals, manufactured by Davis Liquid Crystals, Inc., are rated from 30 to 35 °C. Temperature variations as small as



1.2 °C can be measured with an uncertainty of  $\pm .2$  °C. The test was conducted with natural convection with a surface temperature of approximately 32 °C. Results were consistent with the infrared test with temperatures variations not greater than 1.2 °C across most of the surface. As for the early test, small hot spots were evident near some thermocouple lead wire locations.

### 3. Energy Balance.

An energy balance was performed to determine the heat loss by conduction from the heat transfer test surface used to obtain final results. During the energy balance, heat loss by radiation and convection were prevented since the metal foil surface, ordinarily exposed to convection in the wind tunnel, was covered with three layers of 25.4 mm thick foam insulation. For the energy balance, and for all wind tunnel testing, foam insulation was also placed around the sides of the test surface located below the wind tunnel convection surface. To estimate heat loss through the insulation placed on top of the foil surface, program ENERGB was employed with an algorithm involving the one dimensional, linear form of Fourier's conduction equation:

$$q_w = KA \frac{\Delta X}{\Delta T} \quad (\text{eqn. 2.7})$$

For the insulation, K is 0.4 W/m °C, A is 0.4897 m<sup>2</sup>,  $\Delta X$  is 0.0254 m, and  $\Delta T$  is the temperature drop in the X direction in °C. Heat conduction through the bottom and sides of the heat transfer device is then given by:

$$q_c = VI - q_w \quad (\text{eqn. 2.8})$$

Here,  $V_I$  is the power into the test plate, and  $q_w$  is the conduction loss through the top insulation. Tests were made at five power levels 11.02, 13.0, 15.25, 16.52 and 18.2 Watts, chosen to give conduction losses at the same levels as experienced under normal operating conditions. Figure 8 shows  $q_c$  vs.  $T_w - T_{amb}$  results, where  $T_w$  is the average plate surface temperature. A second order polynomial was fitted to this data in order to predict conduction losses during heat transfer measurements:

$$q_c = 0.683 + 0.954T_{diff} - 0.016T_{diff}^2 \quad (\text{eqn. 2.9})$$

where  $T_{diff} = T_w - T_{amb}$ . This equation is valid over a range of  $T_w - T_{amb}$  from 10 to 30 °C. When exposed to convection in the wind tunnel, conduction losses are only 1.5 to 2.5% of the total power, and thus, a 25% error in the estimate of conduction losses will cause less than a 0.5% error in the estimate of the heat transfer by convection.

Radiation losses were estimated using two different approaches. For the first:

$$q_{ij} = \frac{\sigma(T_w^4 - T_{amb}^4)}{\frac{1 - e_i}{e_i A_i} + \frac{1}{A_i F_{ij}} + \frac{1 - e_j}{e_j A_j}} \quad (\text{eqn. 2.10})$$

and

$$q_{rad} = \sum_{j=1}^n q_{ij} \quad (\text{eqn. 2.11})$$

[Ref. 15]. For the second approach,

$$q_{\text{rad}} = \frac{E_{b1} - J_1}{(1 - \epsilon_1)/\epsilon_1 A_1} = \sum_{j=1}^n \frac{J_1 - J_j}{(A_1 F_{1j})^{-1}} \quad (\text{eqn. 2.12})$$

[Ref. 16]. The view factors,  $F_{ij}$ , for the top and each of the side walls were estimated to be 0.54 and 0.23, respectively [Ref. 16], where

$$\sum_{j=1}^n F_{ij} = 1 \quad (\text{eqn. 2.13})$$

From these two methods, the radiation losses for an average plate temperature of 40 °C were estimated to be 55 Watts, approximately 8.5% of the total power into the heat transfer surface.

#### **4. Contact Resistance Temperature Drop**

Local surface temperatures were measured using thermocouples placed in contact with the underside of the metal foil surface. The junctions of these thermocouples were held in place next to the foil with three layers of 0.254 mm thick double-sided lining tape and RTV silicon rubber epoxy. During the heat transfer tests, temperatures measured by the thermocouples were greater than those of the surface of the plate, due to thermal contact resistance between the thermocouples and the foil and conduction through the foil. The resulting temperature difference  $\Delta T$  is given by:

$$\Delta T = q \left( \frac{1}{h_c A} + \frac{\Delta X}{KA} \right) \quad (\text{eqn. 2.14})$$

where  $\Delta X/KA$  accounts for conduction across the foil thickness and  $1/h_c A$  accounts for the thermal contact resistance.  $q$  is the heat flux through the foil. The contact resistance is highly dependent on the contact pressure as well as the area of the surfaces in contact.

The value of contact resistance used in the present study was the same as used by Joseph [Ref. 3]. In his study liquid crystals were applied to the surface to measure its temperature distribution during convection tests, so that  $\Delta T$  in eqn. 2.13 could be determined. Stanton numbers from baseline tests matched expected correlations after accounting for contact resistance. The empirical relationship for turbulent boundary layers at constant free stream velocity, along a flat plate with constant wall heat flux and unheated starting length of  $\xi = 1.10$  m. [Ref. 14] is given by

$$St_x Pr^{0.4} = 0.030 Re_x^{-0.2} \left( 1 - \left( \frac{\xi}{X} \right)^{0.9} \right)^{-1/4} \quad (\text{eqn. 2.15})$$

Data in Figures 10 and 13 show that this equation matches the data well for  $5 \times 10^5 < Re_x < 2.0 \times 10^6$ . From these measurements, the two terms in brackets in equation 2.13 were estimated to be 0.014  $^{\circ}K/Watt$ . The same value was used for all thermocouples. However, on the present test plate, contact pressure and the area of the thermocouples in contact with the surface varied slightly from one thermocouple to another. Because contact resistance for each individual thermocouple may vary from this value, small deviations in the spanwise heat transfer coefficients and Stanton numbers result, which were independent of flow conditions. In the present study, the effects of these small variations were minimized by presenting results for local conditions in terms of Stanton number ratios.

#### D. TEMPERATURE MEASUREMENT.

All thermocouples employed in the present study are type-T, copper-constantan thermocouples. 120 of these were manufactured by Marchi Associates, Inc and attached beneath of the heat transfer surface. These thermocouples, have a flattened junctions, so that they may be placed in good contact with the surface. One of these thermocouples was calibrated using a temperature regulated bath consisting of liquid nitrogen and electric heaters and a platinum resistance temperature reference ( $\pm 0.01^\circ\text{C}$ ). The calibration was performed over the temperature range of  $0 - 45.32^\circ\text{C}$ . A second order was used to convert microvolts to temperature :

$$T = 0.018205 + 0.025846E - 0.000000581E^2 \quad (\text{eqn. 2.16})$$

where:

$$E = \text{microvolts} \times 10^6 \text{ Volts} \quad (\text{eqn. 2.17})$$

This calibration was used for all Marchi Associates thermocouples attached to the plate, since all thermocouples indicated very similar behavior as temperatures were changed.

Thermocouples manufactured by Omega Engineering Co. were used to measure six plate temperatures, as well as temperatures of the plenum air, freestream air, and the boundary layer as traverses were made. The calibration of Joseph, [Ref. 3.: pp. 37], was first verified, and then used for all of these measurements except the traverses:

$$T = 26.573E - 1.937E^2 + 0.998E^3 - 0.261E^4 \quad (\text{eqn. 2.18})$$

Here,

$$E = \text{millivolts} \times 1000 \quad (\text{eqn. 2.19})$$

Temperatures surveys of  $T - T_\infty$ , were performed using the automated traversing device. For this, two thermocouples manufactured by Omega Engineering were used, after calibration using the technique mentioned above. Simultaneous measurement of free stream temperature was made for every boundary layer location to minimize scatter due to wind tunnel temperature drift. For the thermocouple mounted in the probe that travels the flow field, the following equation was used to convert voltage to temperature:

$$T = 0.1836 + 0.025667E - 0.0000004882E^2 \quad (\text{eqn. 2.20})$$

For the thermocouple used to measure the free stream, the equation employed was :

$$T_\infty = 0.07832 + 0.0231054E - 0.0000006786E^2 \quad (\text{eqn. 2.21})$$

As before,  $E = \text{microvolts} \times 10^6$ . The automated traversing mechanism has two degrees of freedom which allowed measurement of a plane the flow field. Each survey consisted of 800 probe locations, covering an area of 12 cm x 22 cm. Both, spanwise and vertical traversing blocks are mounted on a 20-thread per inch drive screw and two ground steel case hardened steel guide/support shafts. Each drive shaft is directly coupled to a SLO-SYN type

MO92-FD310 stepping motor. Motors are controlled by a MITAS two-axis Motion Controller. Both the motors and the controller are manufactured by The Superior Electric Co. The MITAS controller comes equipped with 2K bytes of memory and a MC68000, 16-bit microprocessor which allows the user to program the start, stop, duration, speed, acceleration and deceleration of the stepping motors.

## **E. DATA ACQUISITION SYSTEM**

The data acquisition system was designed to rapidly measure thermocouple voltages and convert them to temperature in degrees C. Using these temperatures along with user supplied information on ambient conditions, freestream conditions, power input, and flow rates into the injection chamber, the system calculates free stream velocity, density, local heat transfer coefficients, Stanton numbers, spanwise averaged Stanton numbers, and injection parameters such as blowing ratio and discharge coefficient.

### **1. Hardware**

A Hewlett-Packard Series 300, Model 9836S computer, equipped with a MC68000, 8 MHz 16/32-bit processor, dual 5-1/4 inch floppy disk drives, and 1M bytes of memory RAM, was used in the study. The computer was used to process signals from the data acquisition system as well as the information supplied by the user in order to process, store, display and print results. An HP Think Jet printer was used to print data, and an HP 7470 two pen plotter was employed for graphics. Voltages from the thermocouples are read by an HP-3497A Data Acquisition/Control Unit with an HP-3498A

Extender. The unit communicates with the computer through a HP-829737A Interface

## 2. Software.

Programs STANFC1, STANFC2 and ACQTPRO were developed to process temperature and Stanton number data, program ENERGB was developed to estimate the conduction losses, and programs PTSLO, PTSTA, PLSTRVOR, PLSTRTIO, PLSTREC, PLSTVV, SURFCONT and PLOTRUN were developed for plotting data. All these programs are listed in Appendix C. The data files created by the heat transfer programs are listed in Appendix D.

Programs STANFC1 and STANFC2 are modified versions of STDAT1, which was developed by Ligrani, Ortiz and Joseph, [Ref. 3, pp. 41]. Program STANFC1 prompts the user if film cooling is being used. If the answer is affirmative, the program prompts the user to enter the percentage of flow to the injection chamber from the rotometer and the pressure difference between the injection chamber and the static pressure in the wind tunnel. These inputs are transformed to SI units and stored in a data file named "FILD1". The program continues by prompting the user for the stagnation pressure of the free stream (in inches of H<sub>2</sub>O), the ambient pressure (in Hg), the current (Amps) and voltage supplied to the heater. The program then reads the thermocouple voltages and converts them into temperatures. These are then stored in a data file named "TDAFC". After all temperatures have been calculated, the free stream density and velocity are calculated. Parameters previously calculated such as the free stream density, free



stream velocity, ambient pressure, and the power in are stored in a data file named "ID AFC".

Program STANFC2, processes the data files TDAFC, IDAFC and FILDT. The program begins by prompting the user whether a vortex generator is being used or not, then it accounts for conduction, radiation losses and contact resistance. It continues by calculating local heat transfer coefficients and Stanton numbers, average spanwise Stanton numbers and Reynolds number based on downstream distance. These data are printed out and two data files, "STRFCV" and "STAV", are created. In "STRFC" the local heat transfer coefficients and Stanton numbers are stored, along with their spanwise position and downstream positions along the test plate. Spanwise averaged Stanton numbers with their corresponding down stream Reynolds numbers, are located in "STAV". The last section of the program includes a subroutine to calculate film cooling parameters, such as discharge coefficients, density ratios, mass flux ratios, momentum flux ratios and blowing rate.

Program ACQTPRO, developed by Ortiz, acquires temperatures from a thermocouple probe mounted on the automatic traversing device and from another thermocouple that senses the freestream temperature. This program was used to create the data to plot the temperature surveys of  $T - T_{\infty}$ . The program begins by prompting the user for the downstream distance from the boundary layer trip, the number of points in the spanwise direction where temperatures are going to be measured, the number of points in the vertical direction, the spanwise resolution in inches, the vertical resolution in inches and the initial position of the probe with respect to the plate, in both  $Z$

and Y coordinates, in inches. A matrix of data points is then computed. Freestream temperature is calculated and ambient conditions are input. The program then enters a loop which samples each temperature 25 times per probe position and 5 times the free stream temperature. Upon acquiring these temperatures and obtaining their respective average,  $T - T_{\infty}$  is calculated for each probe location. The temperature difference along with their respective coordinates are stored in a matrix. At the end of the data collection run, these values are read into a data file named TPRO on a floppy disk. These data are plotted using program TPROPLOT.

### III. EXPERIMENTAL RESULTS

#### A. **BASE LINE MEASUREMENTS**

Heat transfer measurements were made at free stream velocities of 10 m/s and 15 m/s, without vortex and without film cooling. These were done in order to determine how heat transfer from the plate compares with existing correlations. These measurements validated and qualified the performance of the heat transfer plate and measurements procedures used. Results are given in Figures 9-11 for 10 m/s, and in Figures 12-13 for 15 m/s.

Figure 9 shows the spanwise uniformity of the local heat transfer coefficient of the test surface at 10 m/s. Except for row 1, the spanwise uniformity is very good with maximum variation of 10% (based on the average for a given row). These small variations are probably due to slight differences in the spatial uniformity of the heat transfer test surface, especially differences in the conduction contact resistance between different thermocouples and the metal foil, which comprises the top of the heat transfer plate. Larger spanwise variations for row 1 are believed to be due to multi-dimensional heat transfer by conduction through the leading edge and through the front corners of the test plate in addition to the contact resistance. These variations are not as large as those observed by Joseph [Ref. 3: pp. 45, 77-78].

The spanwise-averaged Stanton Numbers for 10 m/s are shown in Figure 10. Six data points are shown, where each corresponds to a different thermocouple row. The data shows excellent agreement with the empirical

equation for turbulent boundary layers on a flat plate at constant free stream velocity, with constant heat flux and unheated starting length of  $x = 1.10$  m [Ref. 15].

$$St.Pr^{0.4} = 0.030Re_x^{-0.2} \left( 1 - \left( \frac{x}{x_0} \right)^{0.9} \right)^{-0.111} \quad (\text{eqn. 3.1})$$

A survey of  $T - T_\infty$  in degrees Centigrade was obtained at  $X = 1.48$  m, using a calibrated copper-constantan thermocouple, positioned using the automated traversing device. Results are shown in Figure 11, for  $U_\infty = 10$  m/s with no vortex and no film cooling. In this figure, results for an area normal to the flow of 11 cm x 20 cm, are given, as measured using 800 probe positions. The survey evidences good spanwise uniformity of the temperature boundary layer.

Figure 12 and 13 show the spanwise variations of the heat transfer coefficient and averaged Stanton numbers as function of Reynolds number for 15 m/s free stream velocity. Results are consistent with those obtained for 10 m/s. In Figure 12, the data show good spanwise uniformity, except for the first row, where variations are slightly larger than for the 10 m/s case. In Figure 13, the data again show excellent agreement with equation (3.1).

## B. BOUNDARY LAYER WITH SINGLE VORTEX

Heat transfer measurements were made at free stream velocities of 10 m/s and 15 m/s with an embedded longitudinal vortex and no film cooling. These were done to further qualify the heat transfer surface for spatially re-

solved heat transfer measurements. To produce the vortex, vortex generator #2, (see Joseph [Ref. 3: pp 76]), was positioned 0.479 m downstream from the boundary layer trip, and 4.79 cm in the positive Z-direction, as shown in Figure 2.

The spanwise variation of local  $St/St_0$  for 10 m/s and 15 m/s are presented in Figures 14 and 15, respectively. Here,  $St_0$  is the local Stanton number without an embedded vortex. In both of these, the effect of the vortex on wall heat transfer is evident. The Stanton number ratios approach 1 away from the vortex. As Z decreases from +15cm, the ratios increase until maximum values of 1.2 and 1.25 are reached for 10 and 15 m/s, respectively. These maxima correspond to locations on downwash sides of vortices, where secondary flows result in boundary layers which are locally thinner than at other locations. For  $-5.0 < Z < 0.0$  cm a large gradient of heat transfer exists at each downstream location. The location of this gradient moves to smaller Z as the vortex develops downstream. For smaller Z, Stanton number ratios for 10 and 15 m/s, reach minima of 0.92 and 0.90 at locations which correspond to the upwash sides of vortices. Here, the boundary layer is locally thicker than at other locations.

The results in Figures 14 and 15 are in excellent quantitative agreement with those of Joseph [Ref. 3: pp. 87-88], for the same experimental conditions, (The sign of the Z coordinate in this experiment is opposite to the one employed by Joseph). The results in 14 and 15 also show qualitative agreement with the measurements of Eibeck and Eaton [Ref. 6], where small quantitative differences are a result of different vortex generator geometries.

### C. BOUNDARY LAYER WITH FILM COOLING

In order to further qualify the heat transfer surface and the film cooling injection system, measurements were made with film cooling without embedded vortex. Results were obtained at 10 m/s, at  $\theta = 1.614, 1.699$  and  $1.50$  with blowing ratios of 0.68, 0.98 and 1.26 respectively, and at 15 m/s at  $\theta = 1.393$  and  $1.586$  with blowing ratios of 0.47 and 0.86 respectively. Results are presented in Figures 16-30.

Figures 16-18 show the spanwise variations of  $St/St_0$  at 10 m/s, for blowing ratios of 0.68, 0.98 and 1.26, respectively. The first data set was obtained using 13 injection holes, which produce a film wide enough (25.4 cm) to cover the entire span of the measuring heat transfer surface. Because of the limitations on the secondary air supply, 9 and 7 injection holes were required to produce blowing ratios of 0.98 and 1.26, respectively. In these cases the coolant was injected such that it covered a portion of the center span of the heat transfer test surface. Consequently, Stanton number ratios are higher near the edges of the plate, as shown in Figures 17 and 18. The latter Figure for only 7 injection holes, shows this effect to be particularly significant, however, in spite of this a large spanwise uniform area exists in the center portion of the plate where adequate spanwise averages may be obtained. Apart from this, the spanwise uniformity of Stanton number ratios in Figures 16-18 is excellent with a maximum deviation of about 10 percent.

Figures 19 and 20 show the spanwise variations of the Stanton number ratios at 15 m/s. Results for blowing ratios of 0.47 and 0.86 were obtained using 13 and 7 injection holes respectively. Spanwise variations in Figures

19 and 20 are larger than in Figures 16-18, though qualitative trends are very similar.

A summary of spanwise averaged  $St/St_o$  as dependent upon Reynolds number is given in Figure 21. Graphs showing individual curves are presented in Figures 22- 26, where averaged  $St/St_o$  are given for blowing ratios of 0.68, 0.98 and 1.26 at 10 m/s, and 0.47 and 0.86 at 15 m/s, respectively. Referring to Figure 21, the lowest  $St/St_o$  are observed for  $M = 0.68$  at 10 m/s and for  $M = 0.47$  at 15 m/s. For each individual data set, the lowest ratio is present for the two rows of thermocouples nearest the film cooling holes, where  $X/d$  is 7.35 and 17.48. Here,  $X$  is distance from the downstream edge of the injection holes, and  $d$  the injection hole diameter. The data in figures 21-26 are plotted as function of the blowing ratio in figures 27 and 28. Results in 21-28 are qualitatively consistent with the fully turbulent measurements of Goldstein and Yoshida, [Ref. 15], also for a single row of injection holes.

Two surveys of  $T - T_\infty$  in degrees C were obtained in the film cooled turbulent boundary layer at  $X = 1.48$  m,  $X/d = 41.94$ . Both surveys were made at a free stream velocity of 10 m/s, with  $M = 0.98$  and a coolant injection temperature of 51 °C. In one case, the plate was heated to 40 °C (Figure 30.), and in the other, the plate was maintained at the free stream temperature (Figure 29.). The latter experimental arrangement with unheated plate allowed the determination of the presence and distribution of heated film coolant as indicated by higher temperatures. In Figure 30 with a heated plate, the locations of coolant jets are evident as local hot spots near the wall

Comparing these results to ones in Figure 11, without film cooling shows that the thermal boundary layer is about twice as thick.

#### **D. BOUNDARY LAYER WITH SINGLE VORTEX AND FILM COOLING**

In this part of the study the effect of an embedded vortex on a film cooled turbulent boundary layer was studied. This section of the experiment was conducted in four different parts. For all the parts of the experiment the same vortex generator was employed. The first consisted in repeating Joseph data, [Ref. 3, : pp. 97-104]:  $U_{\infty} = 10$  m/s, vortex generator #2 at  $Z = 4.79$  cm and blowing ratio,  $M = 0.68$ , in order to provide additional check on measurements, equipment and procedures. In the second step, a blowing ratio of  $M = 0.98$  was employed, at  $U_{\infty} = 10$  m/s. The position of the vortex was changed to three different locations with respect to test section center line. Vortex position A corresponds to vortex generator at  $Z = 3.52$  cm, vortex position B to  $Z = 4.79$  cm, and vortex position C to  $Z = 6.06$  cm. In the third step, a freestream velocity of 15 m/s, with  $M = 0.47$  were employed, in order to study the effect of blowing ratio. In the fourth part, a blowing ratio of  $M = 1.26$ , at  $U_{\infty} = 10$  m/s was employed, in order to study the effect of high blowing ratio. Here, information was also obtained on changes in boundary layer structure which occurred for higher blowing ratios.

##### **1. Freestream 10 m/s. Blowing ratio, $M = 0.68$ . Repeat of Joseph data.**

These heat transfer measurements were obtained to compare with those of Joseph, [Ref. 3]. He first showed that embedded vortices cause significant changes in heat transfer in film cooled turbulent boundary layers. This finding is also evident from the present study. To obtain the present



data set, vortex generator #2 was placed at position B, and all 13 injection holes were used for film cooling. Results are presented in Figures 31a-31f and in Figure 32. Overall effects are now discussed. The embedded vortex produces a thicker boundary layer in the upwash side thus augmenting the film cooling protection. Near the downwash side, the boundary layer is locally thinner, and the protection provided by the film cooling is minimized. The undercooled region produced on the upwash side vortex is very persistent not only in the down stream direction, but also in the spanwise direction. Here, Stanton numbers are .5 to 5.5 percent lower than those in boundary layers with film cooling only.

Figures 31.a-f., show the spanwise variation of the Stanton number ratios,  $St/St_o$  with film cooling and embedded vortex. Here,  $St$  is the local Stanton number and  $St_o$  is the Stanton number for the same location and free stream velocity but without film cooling and without embedded vortex. A  $St/St_o = 1$  thus indicates an undisturbed thermal boundary layer. As shown in the set of Figures 31.a - 31f, the lowest  $St/St_o$  is 0.55 at  $X = 1.15$  m,  $X/d = 7.35$ , and the maximum is 1.025 at  $X = 2.00$  m,  $X/d = 96.59$ . If these results are compared with those of Joseph [Ref. 3. : pp. 97-103], a general qualitative agreement can be observed. Differences are due to improvements in the present heat transfer test plate, especially better spanwise temperature resolution and more uniform heat flux.

Figure 32. shows surface contours of  $St/St_f$ . Here,  $St$  is the local Stanton number, and  $St_f$  is the local Stanton number at the same location with film cooling but without embedded vortex. A very steep heat transfer gradient is present which is near the same location as the axis of the vortex

At the upstream end of the plate this gradient is located near  $Z = -2$  cm. A hot spot is present at larger  $Z$ , and a region of high heat transfer is present at smaller  $Z$  on the upwash side of the vortex. These results are in qualitative agreement with those of Joseph [Ref. 3, pp. 104], except the most significant hot spots are located further downstream in the present study.

## **2. Free stream 10 m/s, Blowing ratio, $M = 0.98$**

In order to achieve the blowing ratio used for this data, 9 injection holes were employed for film cooling. Here, injection covers the midspan of the test plate from  $-12$  cm  $< Z < 12$  cm. Vortex generator #2, was placed 60 cm upstream of the row of injection holes, at vortex position A, B and C, to investigate the effect of the vortex position with respect to film cooling injection holes. Results are presented in Figures 33 - 42.

### **a. Data overview.**

Spanwise variations of  $St/St_0$  for the vortex position B are shown in Figures 33a-33f. These data show the same overall qualitative trends as measurements at 10 m/s and  $M = 0.68$  (Figure 31). With embedded vortex, the normalized Stanton numbers in 33a-33f are increased on the downwash side and decreased on the upwash side relative to the boundary layer with film cooling only. The only significant quantitative difference between these results and those in 31 are higher  $St/St_0$  at  $X/d = 17.48$  and at  $X/d = 33.59$  resulting from a less effective film cooling at  $M = 0.98$ .

b. Effect of downstream development.

In Figures 33a - 33f, a double peak of  $St/St_0$  is present at  $X/d = 17.48$ , and at  $X/d = 33.59$ . As the boundary layer develops further downstream, one peak becomes smaller ( $Z \approx -2.0$  cm), and one increases in magnitude ( $Z \approx 3.0$  cm), until at  $X/d = 54.50$  the  $St/St_0$  distribution shows one large peak. This  $St/St_0$  peak increases in magnitude to become equal to 1.05, or about 54 percent greater than the  $St/St_0$  with film cooling only.  $St/St_0$  data in Figure 34, indicate that this hot spot covers an area along the center and spanwise downstream half of the plate. Such behavior evidences highly three-dimensional interactions within the boundary layer.

Figure 34 shows the  $St/St_f$  distribution for vortex position B and  $M = 0.98$ . A steep heat transfer gradient is evident along the length of the test surface, which corresponds to the path of the vortex center. This path is at an angle to the streamwise direction, moving to smaller  $Z$  as the vortex convects downstream. Compared to results for  $M = 0.68$  in Figure 32, the heat transfer gradient is steeper, and a larger region where  $St/St_f$  is less than 1 is present over the top third of the test plate. This follows since a larger amount of coolant is swept by the vortex at higher blowing ratio.

For  $Z$  values smaller than those along the location of the vortex center, Figure 33 shows values of Stanton ratios which are about 5 per cent lower than those with film cooling only. The same trend is evident in Figure 34, where almost 1/3 of the plate shows  $0.90 < St/St_f < 0.98$ . These locations are on the upwash side of the vortex, where film coolant seems to be pushed and spread over a very large portion of the plate. Similar phenomena were observed by Goldstein and Chen, [Refs. 2 and 7], in a study of film cooling of

a turbine blade with injection through one and two rows of holes in the near-endwall region.

Figures 35a- 35d show the  $T - T_{\infty}$  temperature field as it develops downstream at  $X/d = 41.9, 82.9, 109.2$  and  $147.0$ . For these tests, film cooling jets were heated to  $51^{\circ}\text{C}$  without providing any heat to the test plate. Thus, the temperature field shows how fluid from the film cooling holes is convected and distorted by the vortex, where higher temperatures indicate greater amounts of coolant. The most dramatic effect evident from Figures 35a-d occurs on the upwash side of the vortex, where coolant is lifted away from the thermal boundary layer which is ordinarily about 4 cm thick with film cooling. At  $X/d = 41.9$  fluid affected by the film cooling is 6.5 cm from the surface, and at  $X/d = 147.0$ , the temperature field is more than 10 cm from the surface. Also, evident are cooler temperatures with downstream development resulting as coolant is convected and diffused. The areas indicated by low  $St/St_0$  and  $St/St_f$  values correspond to  $0 < Z < -5$  cm, where coolant seems lifted from the surface to accumulate in one small area. Figures 35a-d clearly show how the coolant is pushed and spread over an area by the vortex, and how this area increases in size, as the flow convects downstream.

On the downwash side of the vortex, secondary flows cause freestream fluid to be located very near the wall. Here, the thermal boundary layer is greatly thinned and very little effect of the film cooling remains. From Figure 35c for  $X/d = 82.94$ , the local hot spot is located at to  $0 < Z < -5$  cm, which seems to indicate that film coolant is moved to other locations in the boundary layer by the vortex.

In Figure 36, the temperature field is presented for an experiment in which the heat transfer plate is heated to 40 °C and film coolant to 51 °C. The temperature difference contours show the same qualitative trends as in Figure 35. In particular, the positions of many temperature gradients and the dimensions of the area affected by the vortex are about the same. Results in Figure 36 are different from those in 35 since : (1) it is not as easy to discern which part of the temperature field is due to film cooling only, (2) overall temperature differences are larger, and (3) local hot spots corresponding to film cooling locations are more easily discernable every 3 cm starting at  $Z = -12$  cm.

The temperature gradient at  $Z = -14$  cm, corresponds to the spanwise edge of the film cooling for blowing rate of  $M = 0.98$ .

c. Effect of spanwise vortex position.

To study the effect of the vortex position relative to the film cooling injection, the vortex position was changed from A to B to C locations. Distributions of  $St/St_0$  are shown in Figures 33, 37 and 40, distributions of  $St/St_f$  in Figures 34, 38, 41 and distributions of  $T - T_\infty$  are given in Figures 35, 39 and 42. Regardless of the vortex position, the following phenomena were observed : (1) on the upwash side of the vortex a low heat transfer region exists, where  $St/St_0$  is less than for a film cooled turbulent boundary layer only, (2) on the downwash side of the vortex a wide region of high  $St/St_0$  exists, because of thinning of the boundary layer by the vortex, and (3) at  $X/d = 7.4$ , the film cooling dominates the flow and the vortex seems to have very little effect on the heat transfer.

Comparisons of Figures 33, 37 and 40, show that for low  $X/d$  values up to 17.5, a double peak in the  $St/St_0$  distributions is present for vortex positions A and B. At  $X/d = 33.6$  and further downstream for vortex positions A and C, the double peak in  $St/St_0$  distributions starts to grow spanwise enlarging the portion of the plate covered by the hot spot. In these cases  $St/St_0$  peaks are not as high as for the vortex position B case (Figure 33). A maximum  $St/St_0$  of 1.05 was observed for the vortex position B at  $X/d = 96.6$ , or about 30 percent greater than the  $St/St_0$  with film cooling only. Low  $St/St_0$  and  $St/St_f$  regions on the upwash side of the vortex were observed for all three vortex positions. These were less significant for position C, while varying between 2– 6 percent for the other two vortex positions.

$St/St_f$  distributions from Figures 34, 38 and 40 show that the location, shape and size of the hot spot vary depending on the vortex spanwise position. In Figure 34, for vortex position B, this hot spot is located from the middle length of the plate, growing in size as the vortex develops downstream. For vortex position A, the hot spot is shifted upstream and is not as wide, nor as long as for position B. For vortex position C, the hot spot begins early upstream but persists further downstream, but it does not reach the end of the test section, and it is very narrow. A region of high heat transfer is observed in all three cases, but this area is larger for vortex position A, covering about 2/3 of the test plate. A heat transfer gradient is aligned along the vortex center for all three vortex positions, but it is steeper and more persistent for vortex position B. The region of low heat

transfer, where  $St/St_f$  is less than 1, is largest for position B and smallest for position C.

Figures 35, 39 and 42 show the  $T - T_\infty$  temperature field in degrees C for  $X/d = 41.9$ . For these results the heat transfer plate was maintained at the freestream temperature and the coolant was heated to 51 °C (unheated plate). Overall qualitative trends for all three vortex positions are similar: coolant is lifted away the wall by the upwash side of the vortex; on the downwash side of the vortex, secondary flows cause the freestream fluid to be located very near the wall, making the boundary layer very thin and minimizing the effect of the film cooling. A significant spanwise gradient in temperature exists which is located near the vortex core, and extends about 5 cm from the wall. As expected, the spanwise location of this gradient changes with vortex position. The effect of the downwash side of the vortex is most significant for vortex position B. For this case Figure 35a shows that the boundary layer is thinned such that it only extends 2 cm from the wall. Significant changes also occur near the upwash side of the vortex where secondary flows from the vortex convect film coolant away from the wall. The most significant changes in this part of the flow occur for vortex position C.

### **3. Free stream 15 m/s, blowing ratio, $M = 0.47$ . Effect of low blowing ratio.**

Measurements were made at  $U_\infty = 15$  m/s, with a blowing ratio  $M$  of 0.47, in order to determine the effect of low blowing ratio on heat transfer. These tests were also conducted to obtain additional verification of general conclusions from results obtained at 10 m/s and  $M = 0.98$  blowing ratio. For these tests, vortex generator #2, was used at positions A, B and C.

Results are shown in Figures 43 – 48. Distributions of  $St/St_o$  are shown in Figures 43, 45, and 47, and distributions of  $St/St_f$  are given in Figures 44, 46, and 48.

From a general qualitative point of view, the results at 15 m/s and  $M = 0.47$  are similar to those of 10 m/s and  $M = 0.98$ . The most significant quantitative difference is that  $St/St_o$  maxima are higher, and  $St/St_o$  minima are lower for  $M = 0.47$ . In addition, the peaks of local heat transfer seem to increase more rapidly with downstream distance. At the downstream end of the plate where  $X/d = 96.6$ , local  $St/St_o$  for  $M = 0.47$  may be as high as 1.12 compared to about 1.05 for  $M = 0.98$ . The rapid downstream growth of these maxima becomes more apparent when one considers the film cooled boundary layer alone, since  $St/St_o$  ratios at  $M = 0.47$  are lower than those at  $M = 0.98$ .

At  $M = 0.47$ , the effect of changes in the spanwise position of the vortex are much less significant than at  $M = 0.98$ . At higher blowing ratio, many quantitative changes in the local heat transfer result as the vortex position is changed. In particular, primary and secondary peaks of  $St/St_o$  were observed at  $X/d = 17.5$  and 33.6 for vortex position B, and  $X/d = 54.6$  and 75.6 for vortex position C. At the  $M = 0.47$  blowing ratio, the shapes of  $St/St_o$  distributions for different vortex positions are very similar, especially for  $X/d = 54.6$ , 75.6 and 96.6. Generally, quantitative changes for  $M = 0.47$  occur only in the spanwise locations of the  $St/St_o$  maxima and minima. At  $X/d = 7.4$ , the effect of the vortex position changes is minimal and the spanwise heat transfer rates are mostly affected by the film cooling. At  $X/d = 17.5$  both primary and secondary  $St/St_o$  peaks are present for all three



vortex positions. The only significant  $St/St_o$  changes with vortex position occur at  $X/d = 33.6$  where a small secondary  $St/St_o$  peak is observed when the vortex is located at position A only. Such behavior indicates that the effects of film cooling at  $M = 0.47$  do not persist as far downstream as at higher blowing ratios. In addition, the vortex seems to more completely dominate the flow field as the blowing ratio decreases.

#### **4. Free stream 10 m/s, blowing ratio, $M = 1.26$ . Effect of high blowing ratio.**

In order to study the effect of high blowing ratio on the film cooled turbulent boundary layer with embedded vortex, measurements were made at  $U_\infty = 10$  m/s, with  $M = 1.26$  and the vortex at position B. Results are shown in Figures 49- 52.

The  $St/St_o$  and  $St/St_f$  data in 49 and 50 show the same overall qualitative trends shown by measurements at  $M = 0.98$ , 0.47, and 0.68 augmented heat transfer near the downwash side of the vortex and reduced heat transfer near the upwash side. Also, at  $X/d = 7.4$ , film cooling rather than the vortex dominates the spanwise variation of heat transfer. The most important quantitative differences between these results and those at other blowing ratios are the magnitudes of  $St/St_o$  with film cooling only. Figure 26 shows  $M = 1.26$   $St/St_o$  data at 10 m/s which is, on the whole, greater than data at  $M = 0.68$ , but just lower than results for  $M = 0.98$ . Results presented in Figure 49 reflect the same overall trends.

Details of the spatial variations of normalized Stanton numbers in Figures 49 and 50 are now discussed. At  $X/d = 17.5$ , 33.6 and 54.6 double peaks in  $St/St_o$  distributions are present. These seem to result from inter-

action between cooling jets and the vortex, occurring at  $Z = -2 - -3$  cm and at  $Z = 2 - 3$  cm.

Contours of  $T - T_{\infty}$  ( $^{\circ}\text{C}$ ), at  $X/d = 41.9$  in Figure 51 show that the peak near  $+2-3$  cm results from the downwash of free stream fluid to near wall regions by the vortex. The corresponding  $St/St_0$  peak increases in magnitude as the the boundary layer convects downstream reaching magnitudes as high as 1.05 at  $X/d$  75.6 and 96.6. At these downstream locations augmented  $St/St_0$  cover a large spanwise portion of the film cooled test surface extending from  $-5$  cm to  $+5$  cm (Figures 49 and 50). Magnitudes of  $St/St_0$  maxima in these hot spots at  $M = 1.26$  are about the same as those at  $M = 0.98$ .

Figure 50 shows the heat transfer rate over the test plate in terms of  $St/St_0$ . Here, the hot spot is located from  $X/d = 54.6$  to  $X/d = 96.6$ . This region is very large, confined to the downwash side of the vortex. The temperature gradient on the upwash side of the vortex is not very steep in some streamwise locations. A comparison between Figure 50 and Figure 32 where  $M = 0.68$ , show that, the hot spot is present at the same spanwise and streamwise location in both cases, but in 50 the hot spot is thinner, and the area of low  $St/St_0$  on the upwash side of the vortex is larger.

Temperature contours at  $X/d = 41.9$  in Figure 51, show that the  $St/St_0$  peak at  $Z = -2--3$  cm, lies beneath a region of large temperature gradients very near the vortex center. Figure 52d, shows strong secondary flows at this location which apparently sweep coolant further from the vortex center (to smaller  $Z$ ), such that it collects near  $-5 \leq Z \leq -8$  cm. Contours of vorticity magnitude, calculated from these secondary flow vectors for  $M =$

1.26 vortex position B, are shown in Figure 52e. These show that (1) the core of the primary vortex is located at  $Z = -2$  cm.,  $Y = 3.5$  cm., and (2) that the secondary peak in heat transfer is not a result of any form of secondary vortex. Augmented mixing is initially created by the secondary flows beneath the vortex center, resulting in locally higher heat transfer. This secondary peak shown in Figure 49 at  $X/d = 17.5, 33.6$  and  $54.6$  eventually becomes indistinguishable at larger  $X/d$  equal to  $75.6$  and  $96.6$ . The secondary peak is bigger and more persistent than at  $M = 0.98$ , indicating that the shear layer interaction causing higher heat transfer is dependent upon the mass flux of film cooling.

Another important feature of the results in Figure 51 is the gradient of heat transfer present at  $Z = -10$ – $-12$  cm. for  $0 < Y < 5.0$  cm. This gradient is present at the edge of the film cooled region : coolant was injected from only 7 holes extending across a span from  $-9$  cm. to  $+9$  cm.

Additional flow field information at  $X = 1.48$  m,  $X/d = 41.9$  is given in Figures 52a.–c for  $10$  m/s,  $M = 1.26$  and vortex position B. Data was taken using a five-hole pressure probe, [Ref. 1.: pp. 14-15], to measure pressure at 800 points in a spanwise plane in order to further investigate the effect of the high blowing ratio in the turbulent boundary layer with embedded vortex. These results are consistent with those of Evans, [Ref.1]. They show : (1) that high velocity, high total pressure fluid is swept near the wall on the downwash side of the vortex, (2) a velocity and total pressure deficits exist at the center of the vortex, and (3) low velocity fluid is swept away from the wall near the upwash side of the vortex. Vorticity contours in 52e. show a

large region of negative vorticity in the upwash region,  $(-8 < Z < -4 \text{ cm})$ . In addition, two other regions of negative vorticity result from the secondary flows present.

#### **IV. SUMMARY AND CONCLUSIONS.**

Heat transfer measurements were made of turbulent boundary layers with film cooling and embedded vortices for freestream velocities of 10 and 15 m/s . To obtain the data, a heat transfer test surface was designed and developed to provide constant heat flux over its area, with 126 embedded thermocouples for detailed spanwise resolution of temperature. Extensive qualification tests show that the surface gives excellent spatially resolved heat transfer coefficients over an area of 43.815 cm x 1111.76 cm.

Baseline measurements show excellent agreement with Stanton number correlations for a flat plate with constant wall heat flux and unheated starting length. Results of turbulent boundary layer with embedded vortex show excellent agreement with Joseph, [Ref. 3], and with the literature. Results of turbulent boundary layer with film cooling at different blowing ratios show expected trends, consistent with the data of Goldstein and Yoshida, [Ref. 18].

Longitudinal vortices cause significant changes in heat transfer and structural characteristics of film cooled turbulent boundary layers. Heat transfer augmentations as large as 30 percent, and reductions as high as 10 percent were observed to persist as many as 23 boundary layer thicknesses or 96 film cooling hole diameters downstream of film cooling injection locations. The effects of the embedded vortex on heat transfer in film cooled boundary layers are significant and important :

- 1.) Near the downwash side of the vortex the heat transfer is augmented, vortex effects totally dominate the flow behavior, and the effects of

the film cooling are negated. " Hot spots " will exist for blowing ratios ranging from 0.47 to 1.26, and vortex circulation to freestream velocity ratios of about 1.6 cm.

- 2.) Near the upwash side of the vortex, the coolant is lifted off the wall and pushed to the side of the vortex, increasing the surface area protected by the film cooling.
- 3.) Changing the position of the vortex with respect to the film cooling jets results in significant local quantitative changes in heat transfer occur, even though the overall qualitative trends remain unchanged.
- 4.) Near film cooling injections locations for  $X/d$  up to 7.4, the film cooling dominates the flow behavior and the vortex seems to have very little effect on spanwise variations of heat transfer.

Results (1) and (2) are mostly a consequence of the intense secondary flows produced in the plane perpendicular to the axis of mean vorticity. These results are consistent with those obtained by Joseph, [Ref. 3.: pp. 54], and Evans, [Ref. 1.: pp. 28].

At high blowing ratios:

- 1.) A double peak in the  $St/St_o$  distributions was observed to occur between  $X/d = 7.4$  and  $54.6$ .
- 2.) The change in spanwise position of the vortex in relation with the film cooling jets affects the magnitude, shape and spanwise position of  $St/St_o$  peaks, and
- 3.) Secondary  $St/St_o$  peaks become higher in magnitude and more persistent with respect to downstream development as the blowing ratio increases. The double peaks observed at  $M = 1.26$  were not due to a secondary vortex, but to an interaction between the vortex and film cooling which depends on blowing ratio.

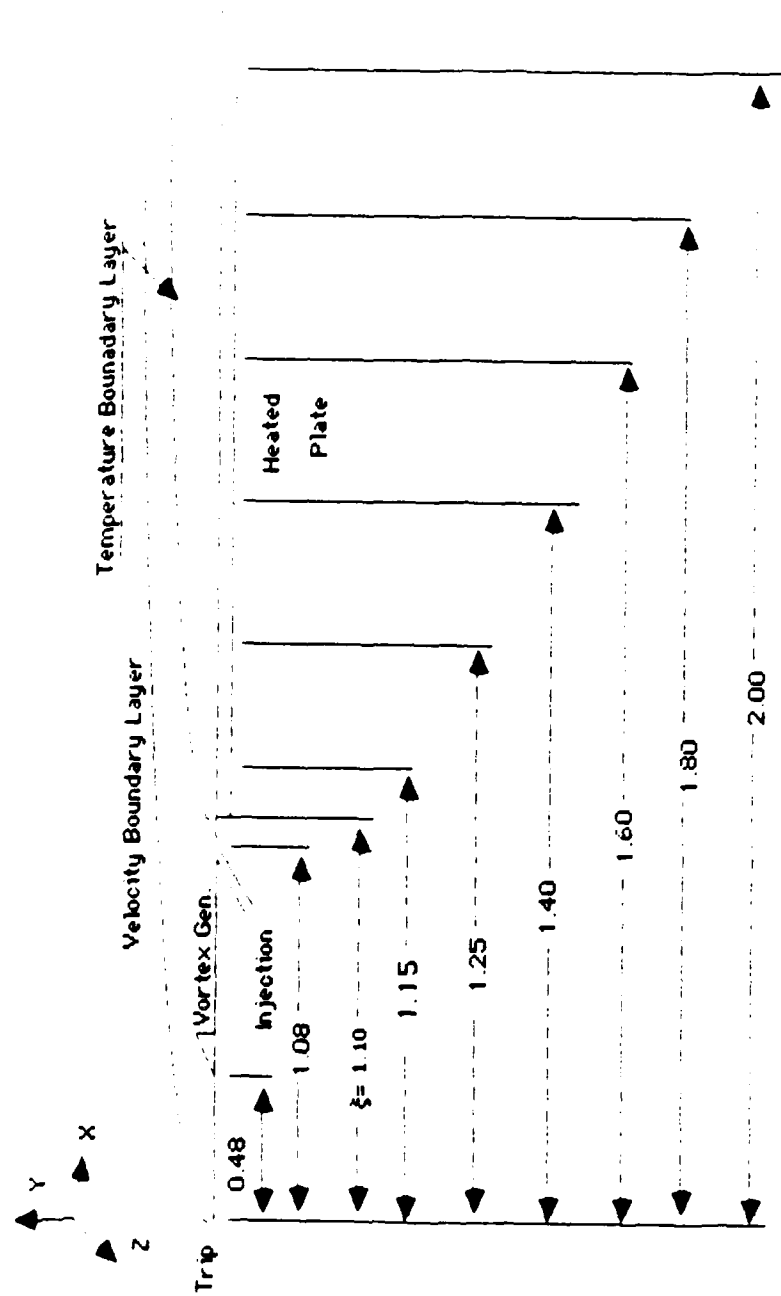
At low blowing ratios:

- 1.) The change in spanwise position of the vortex has very little effect on local heat transfer distributions except to change the locations of Stanton number minima and maxima, and
- 2.)  $St/St_0$  distributions exhibit only one peak which increases in magnitude with downstream development.

It is recommended that flow visualization study of the interaction of the vortex and film cooling be conducted in order to enhance the understanding of some of the complex phenomena observed during the course of this study.

# APPENDIX A

## FIGURES

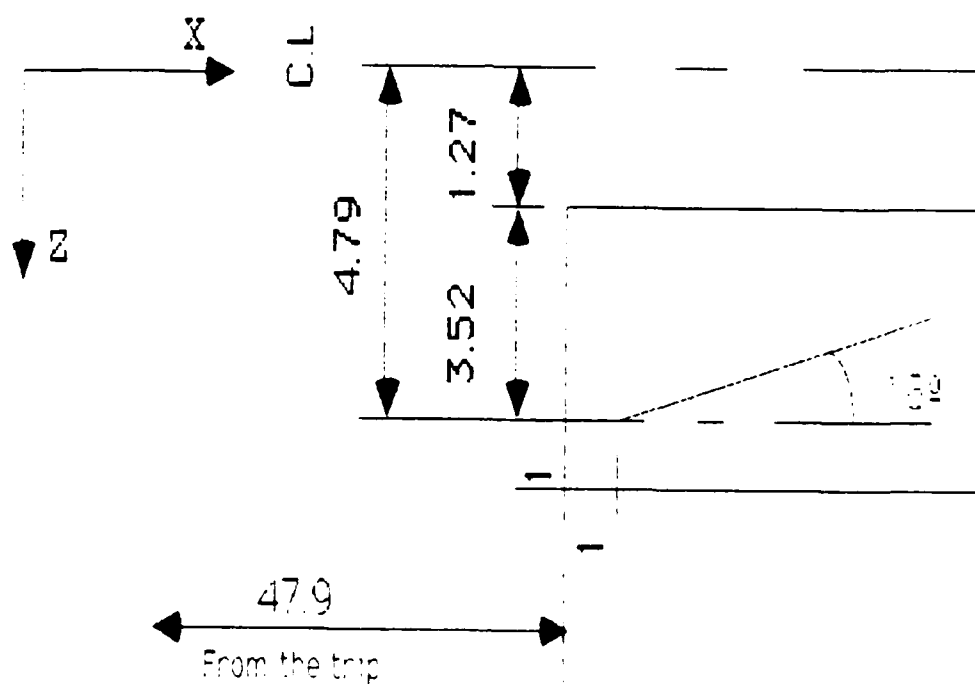


ALL DIMENSIONS IN METERS

Fig 1. Coordinate System of the Test Section



## VORTEX GENERATOR #2 POSITION



All Dimensions in cm.

Fig. 2. Vortex Generator Position.

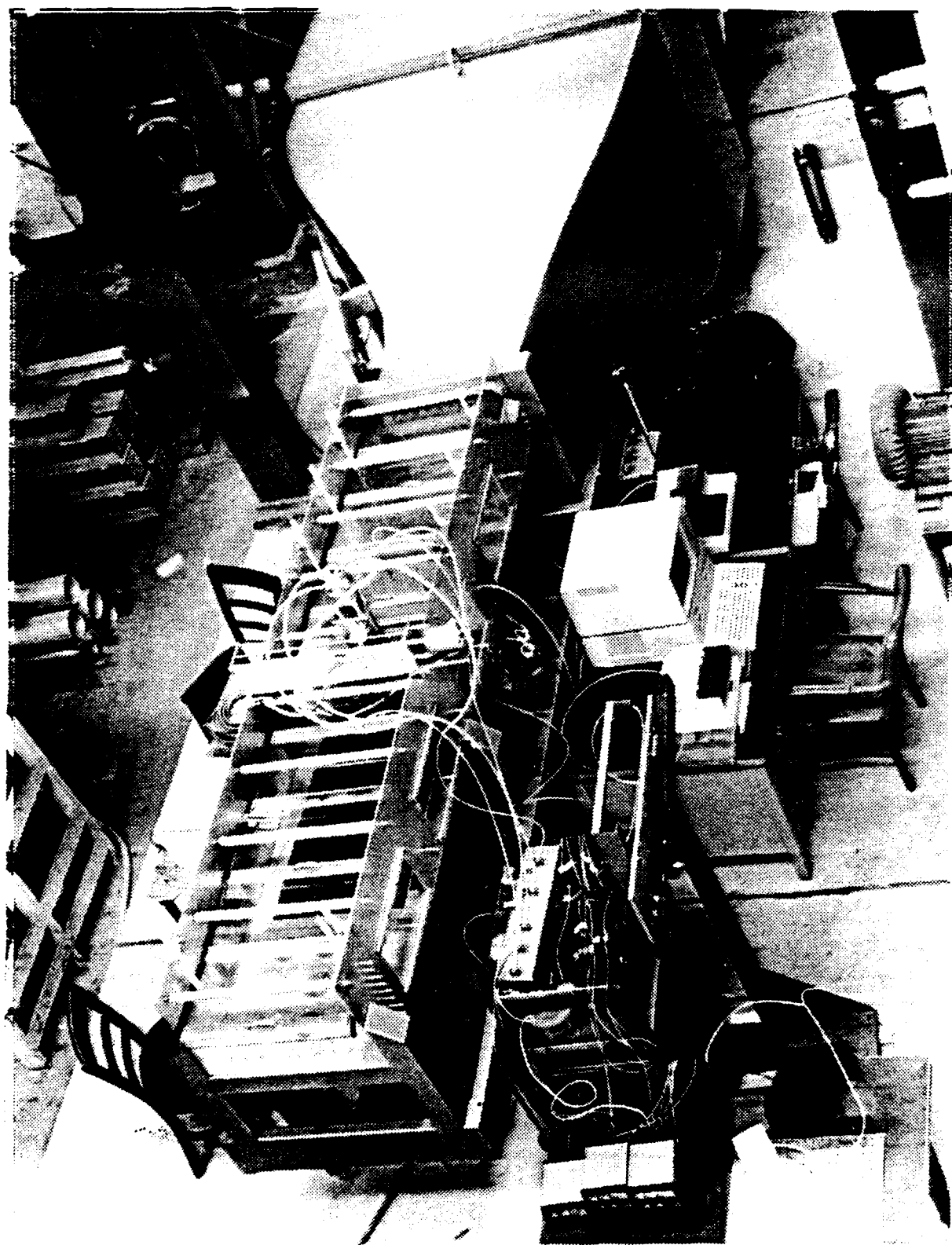


Fig. 3a. Experimental Set-up

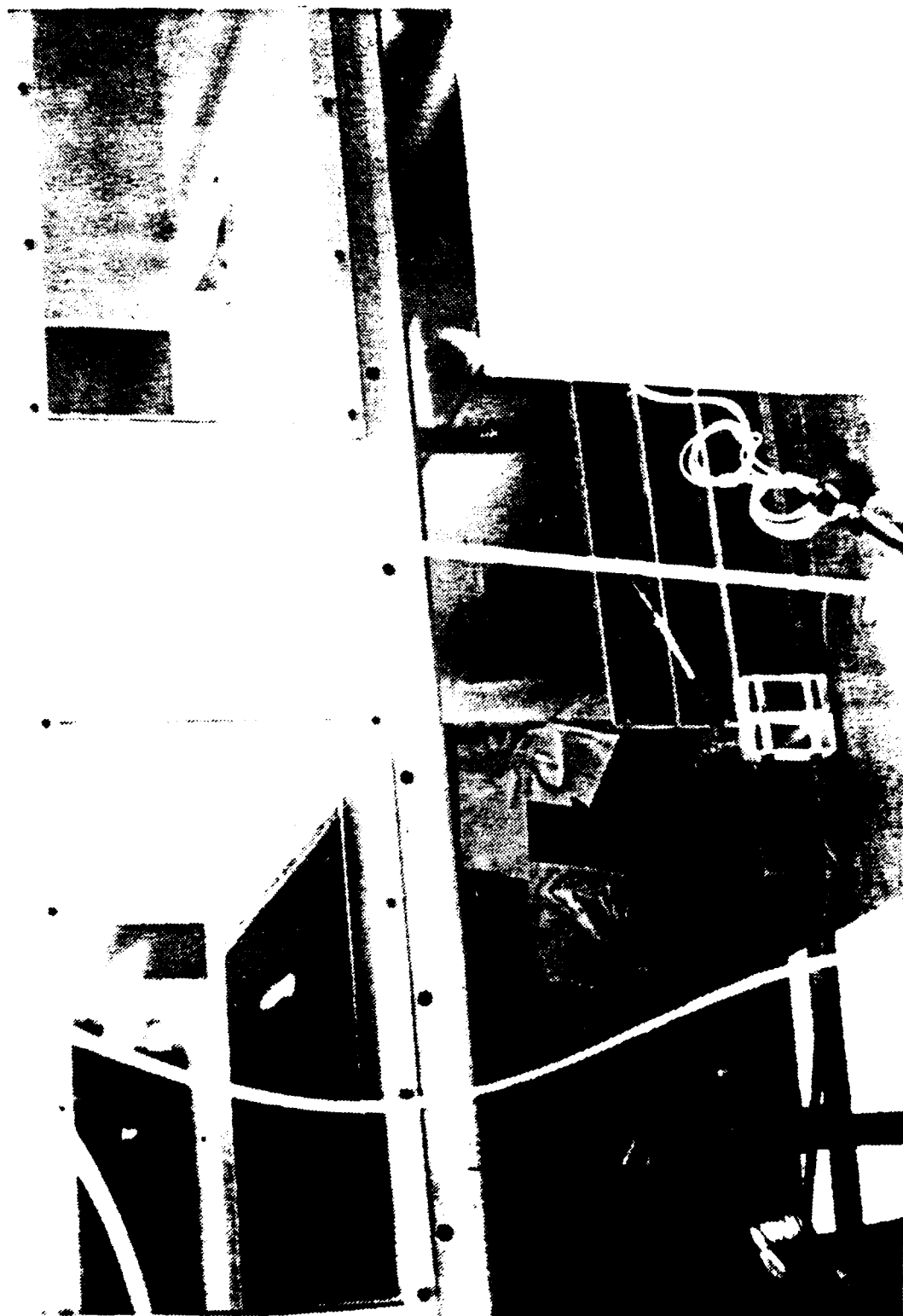
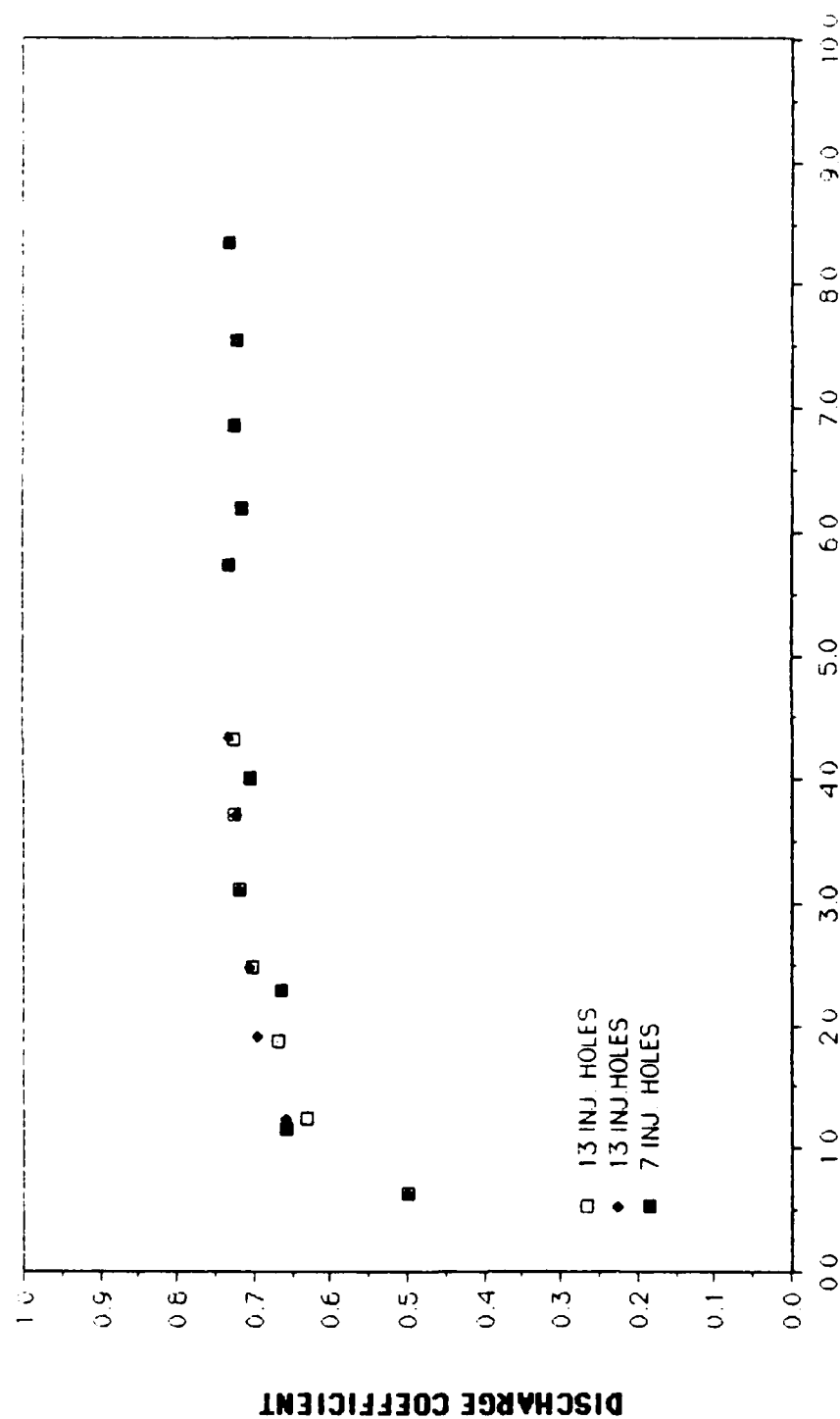


Fig. 3b. Detail of the Injection Plenum and Vortex Generator

# CD VS. REYNOLDS NUMBER



**REYNOLDS NUMBER \* L + 3**  
Fig. 4. Discharge Coefficient vs. Reynolds Number

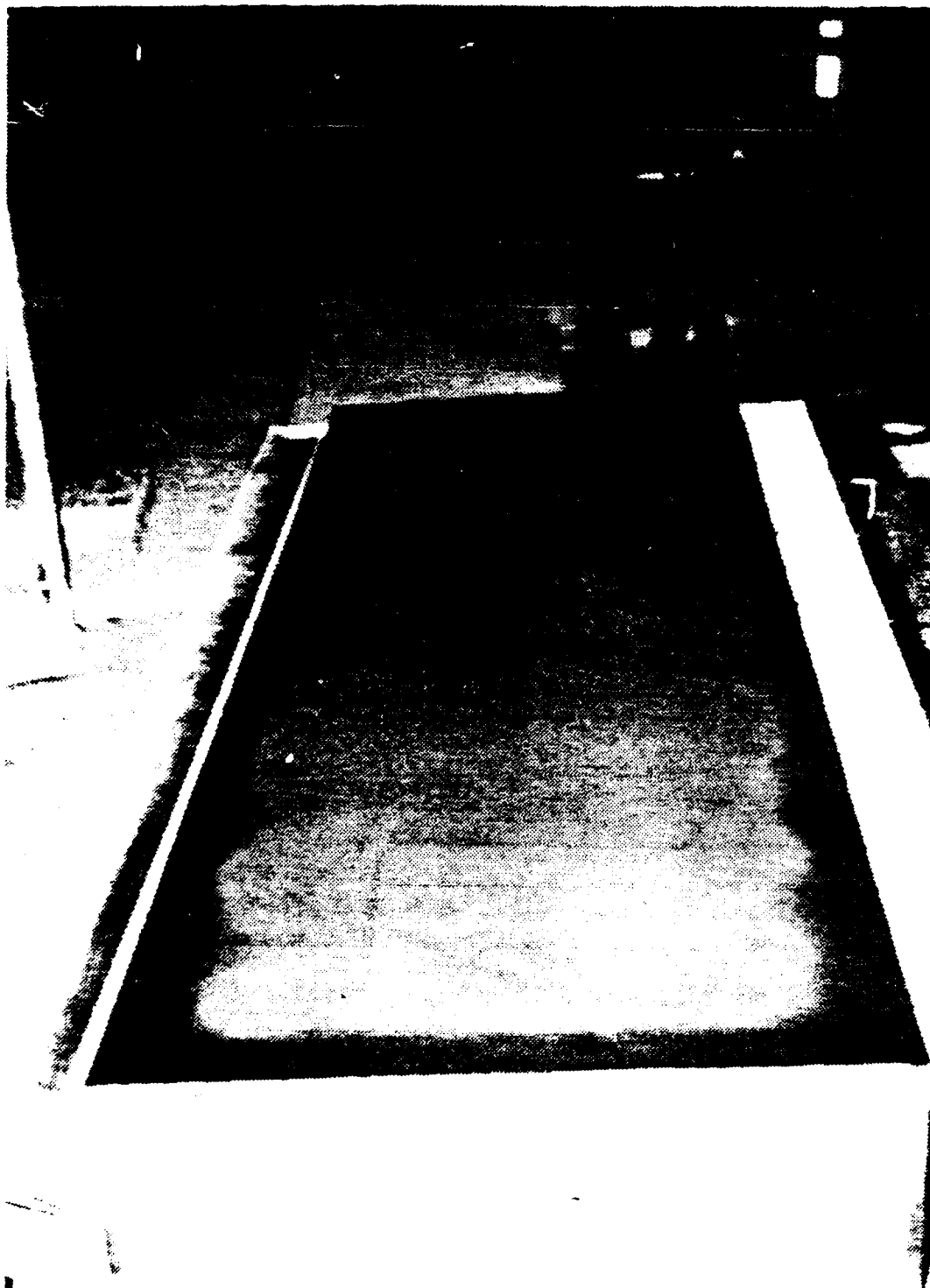


Fig. Sa. Heat Transfer Test Plate

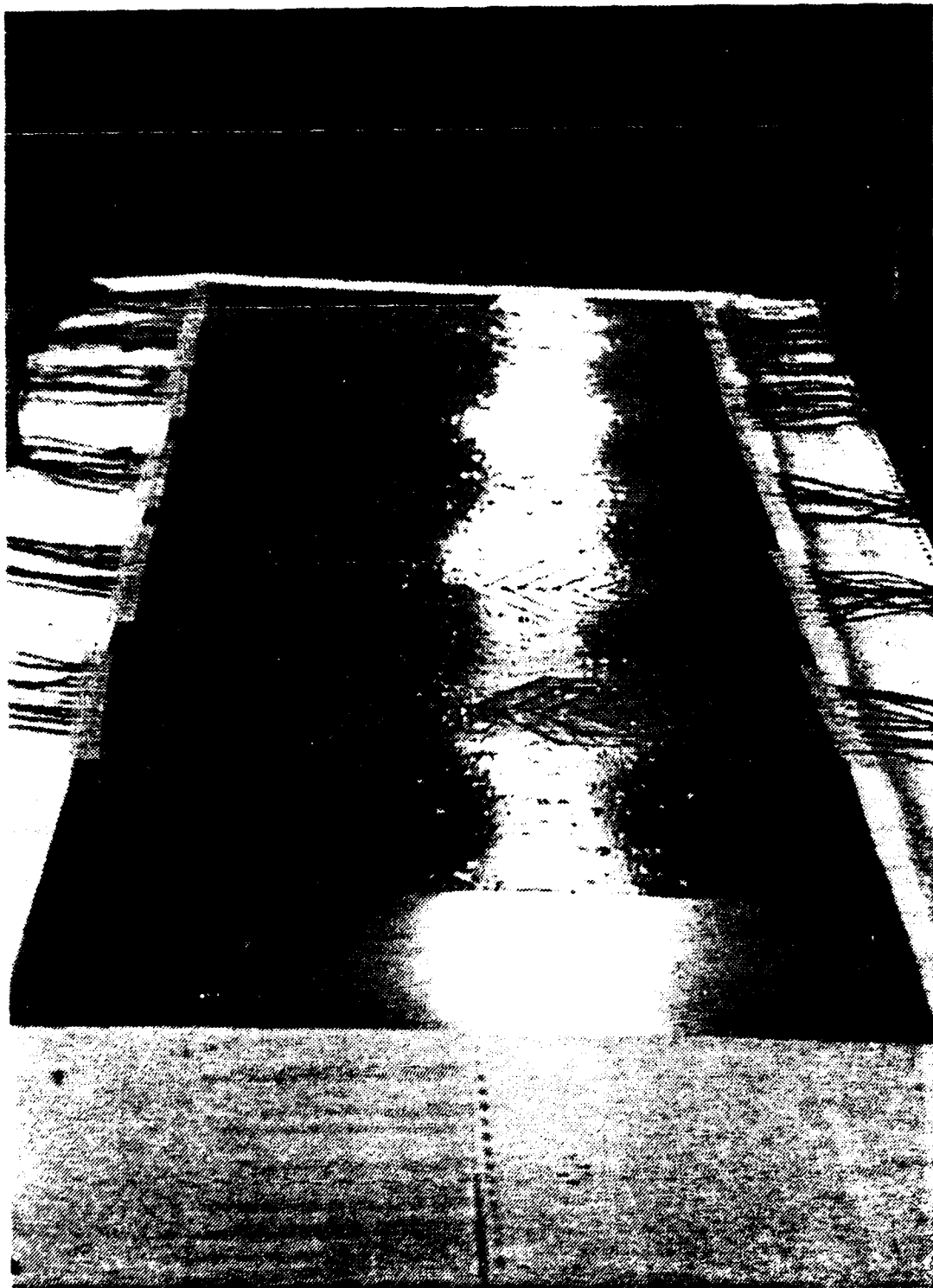
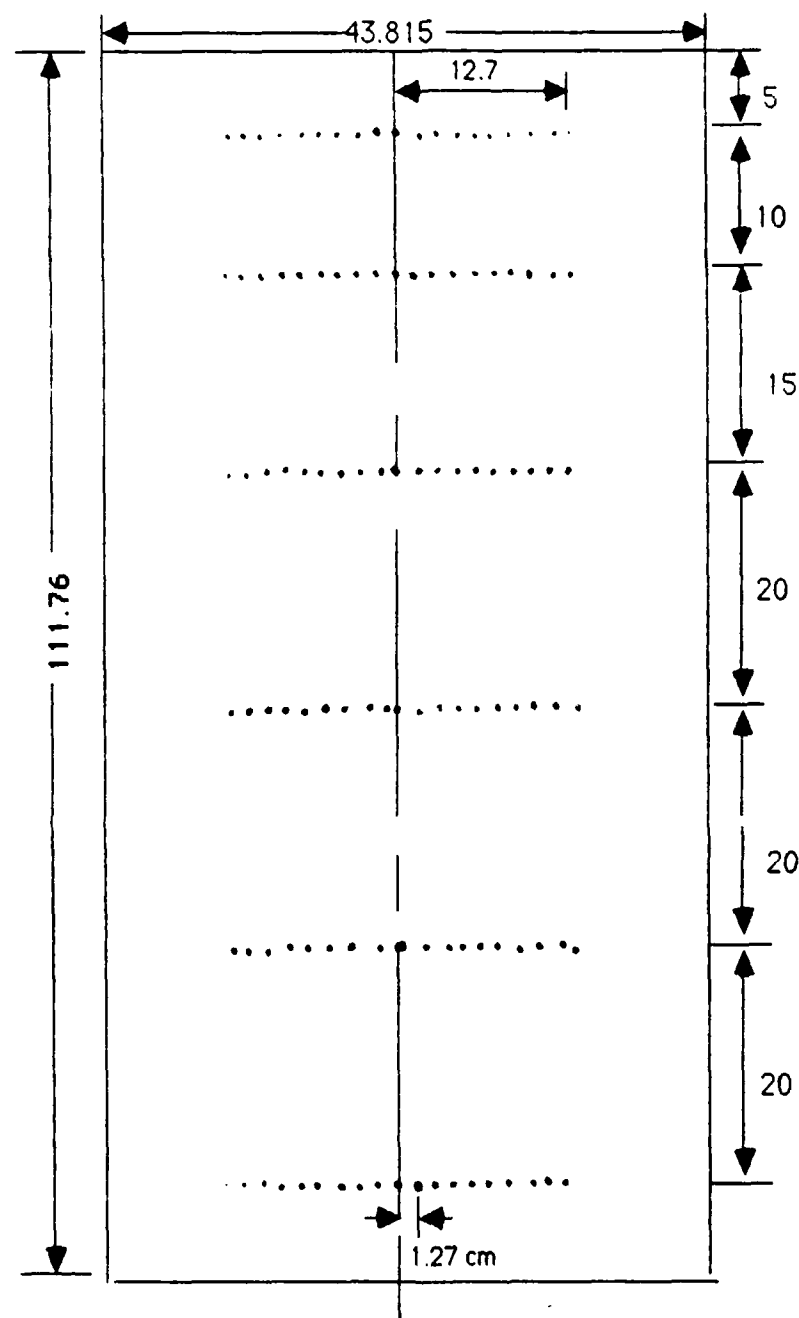
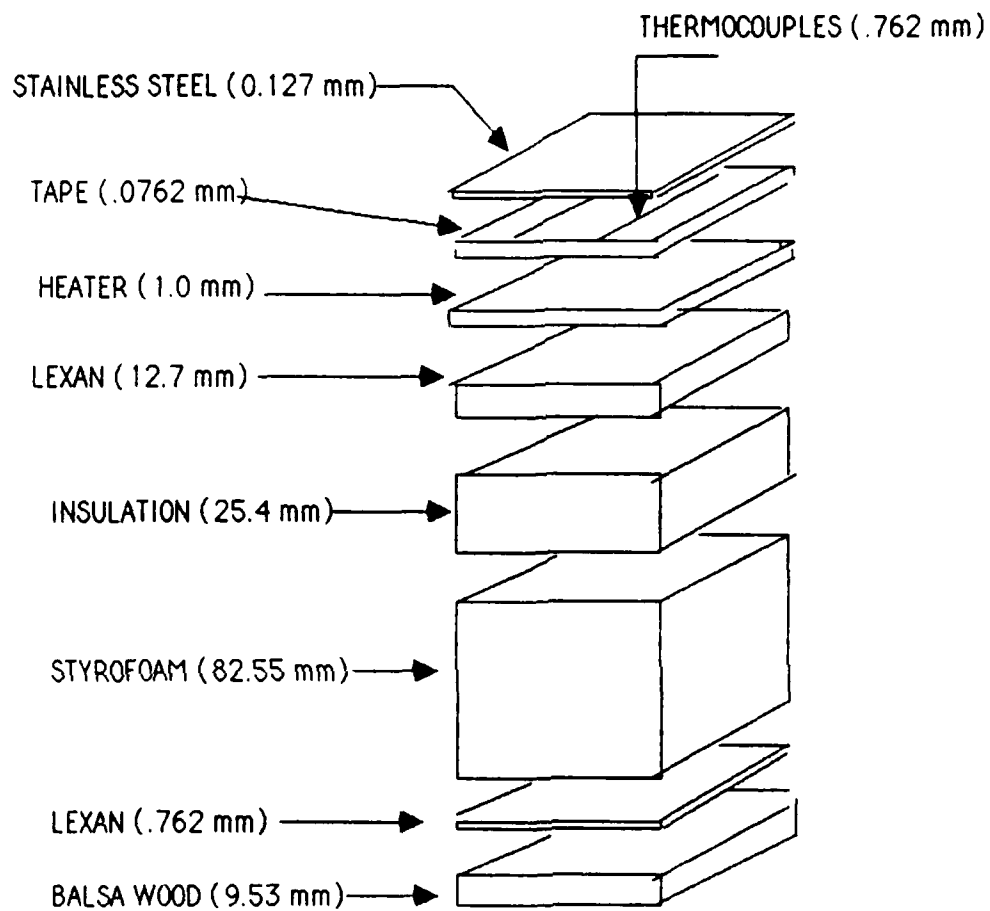


Fig. 5b. Detail Of Heat Transfer Plate



All dimensions in cm.

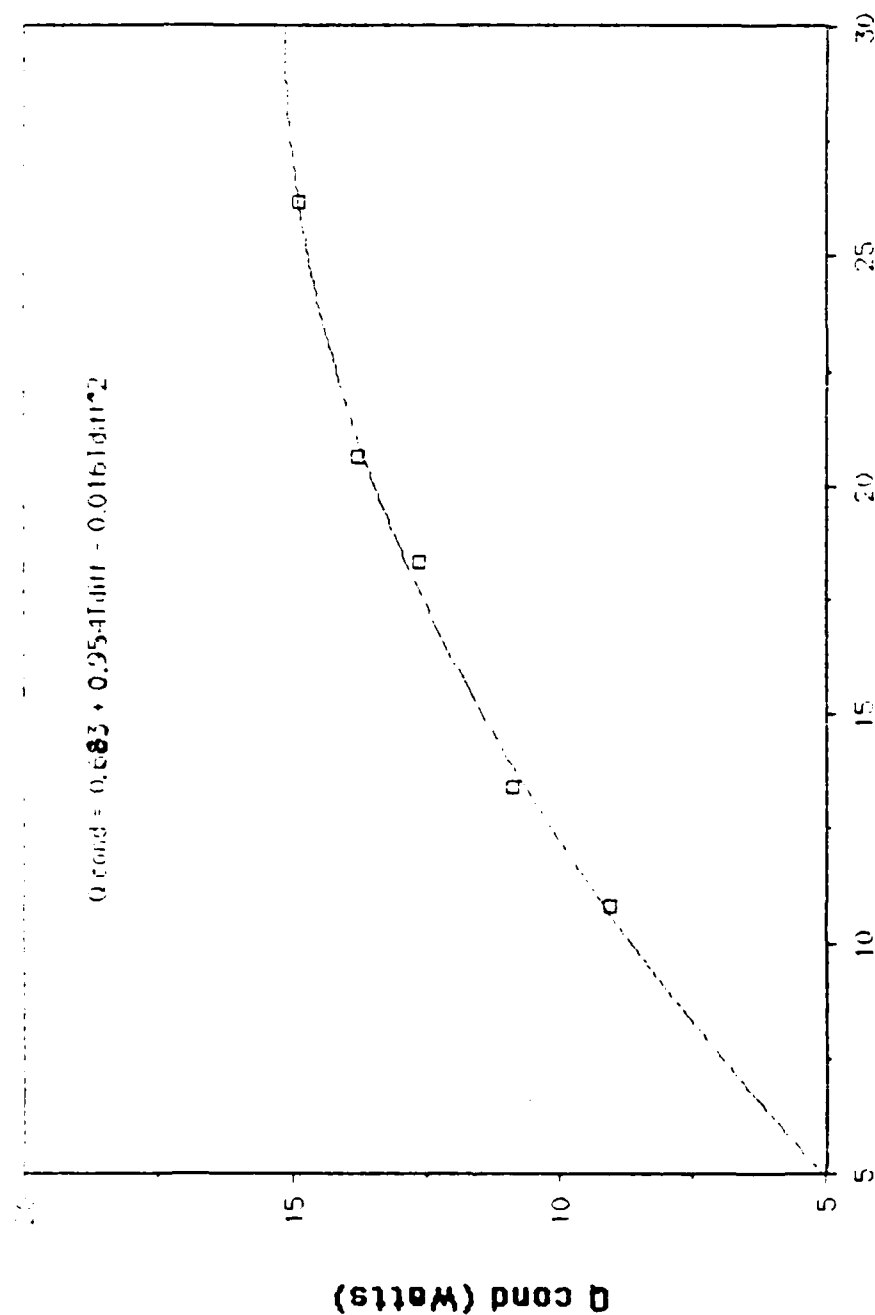
Fig. 6. Thermocouple Placement on Plate



**Fig. 7. Cross Section of Test Surface**



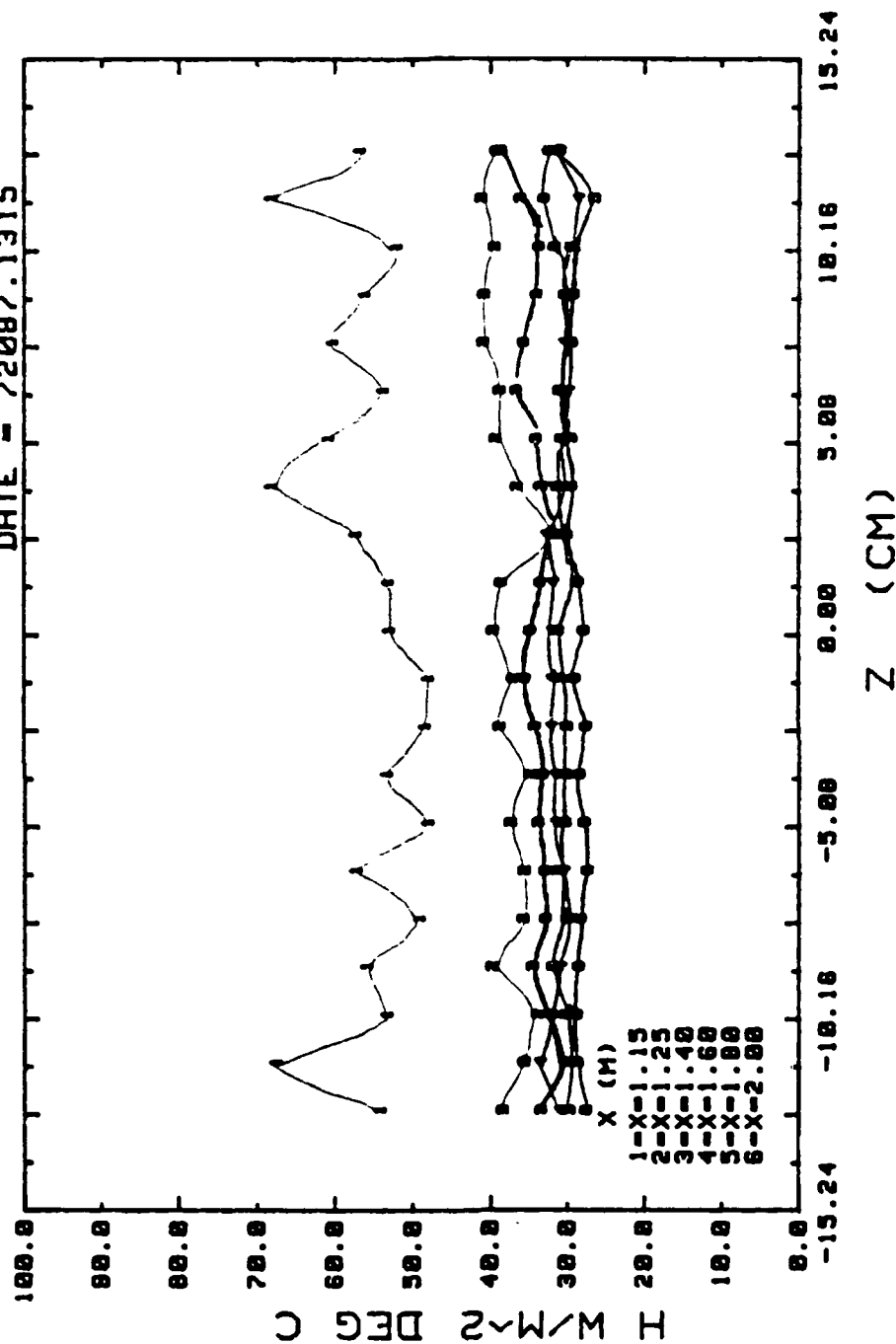
# CONDUCTION LOSSES



Temp. Plate - Temp. Amb (°C)  
Fig. 8. Conduction Losses

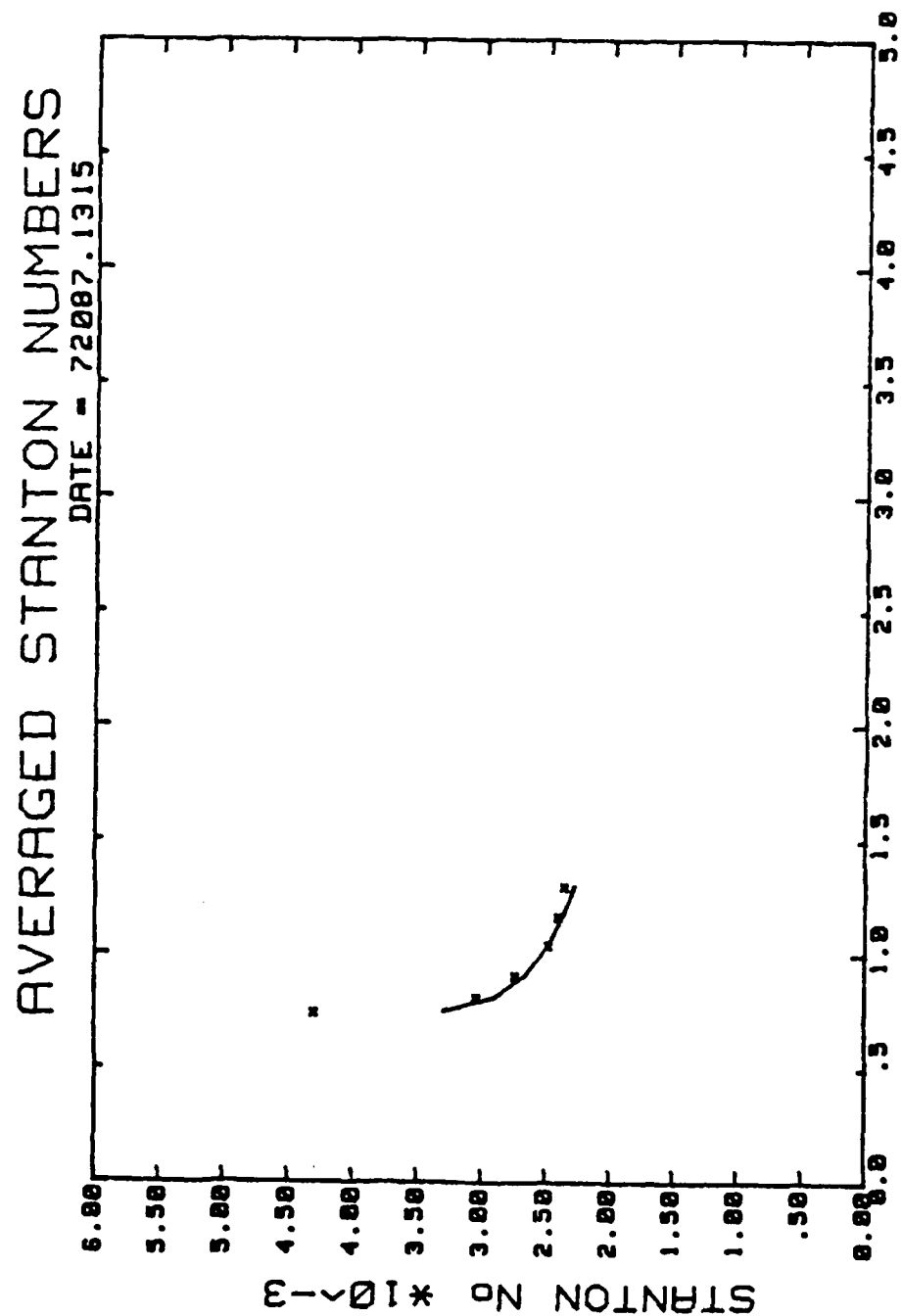
# SPANWISE HEAT TRANSFER COEFFICIENT

DATE - 72087.1315



FREE STREAM 10 M/S, NO FILM COOLING

Fig. 9. Spanwise Variation of Heat Transfer Coefficients.



REX \*  $10^6$   
FREESTREAM 10 M/S, NO FILM COOLING

Fig. 10. Spanwise Averaged Stanton Numbers.

# TEMPERATURE PROFILES

DATE- 81387.1650

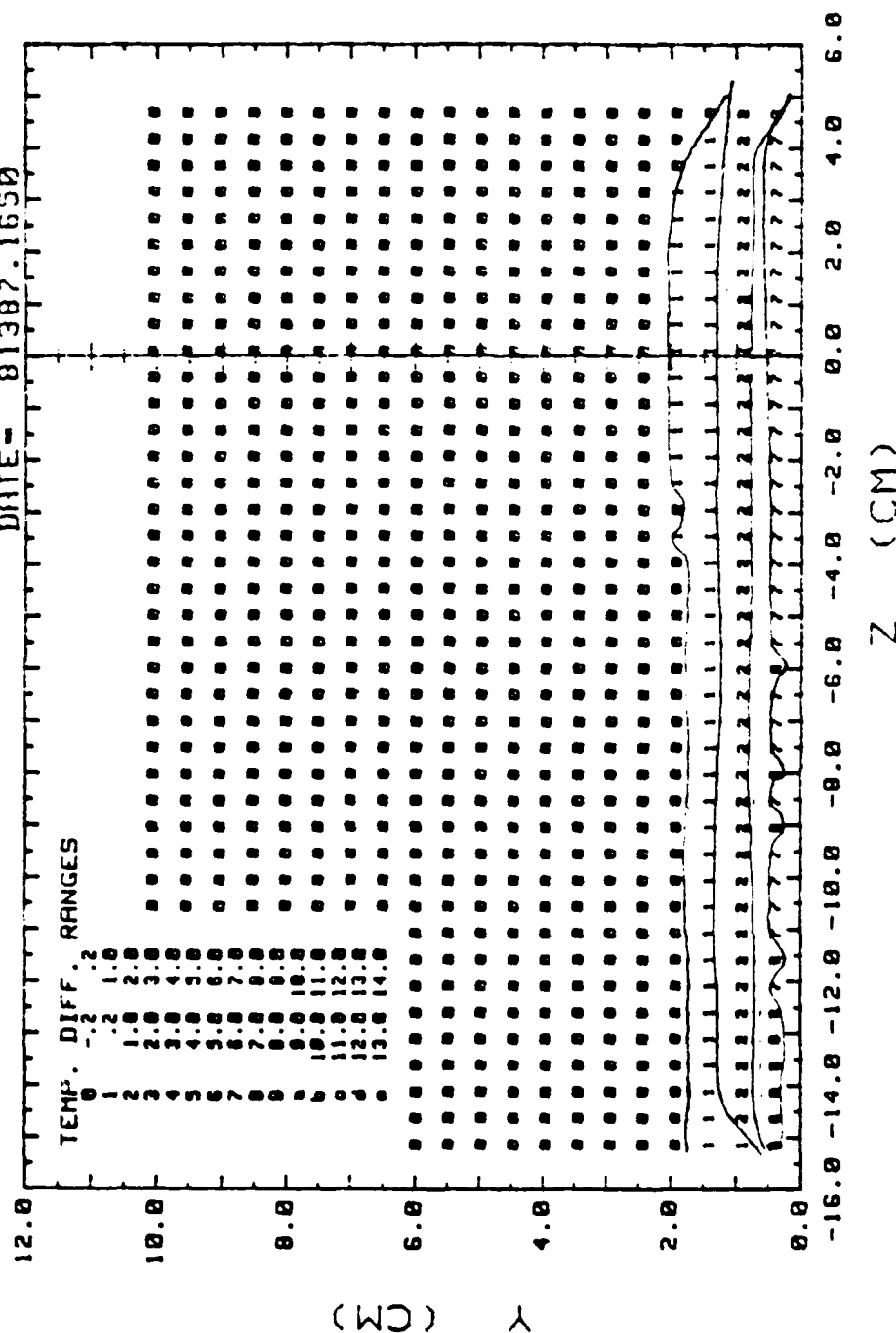
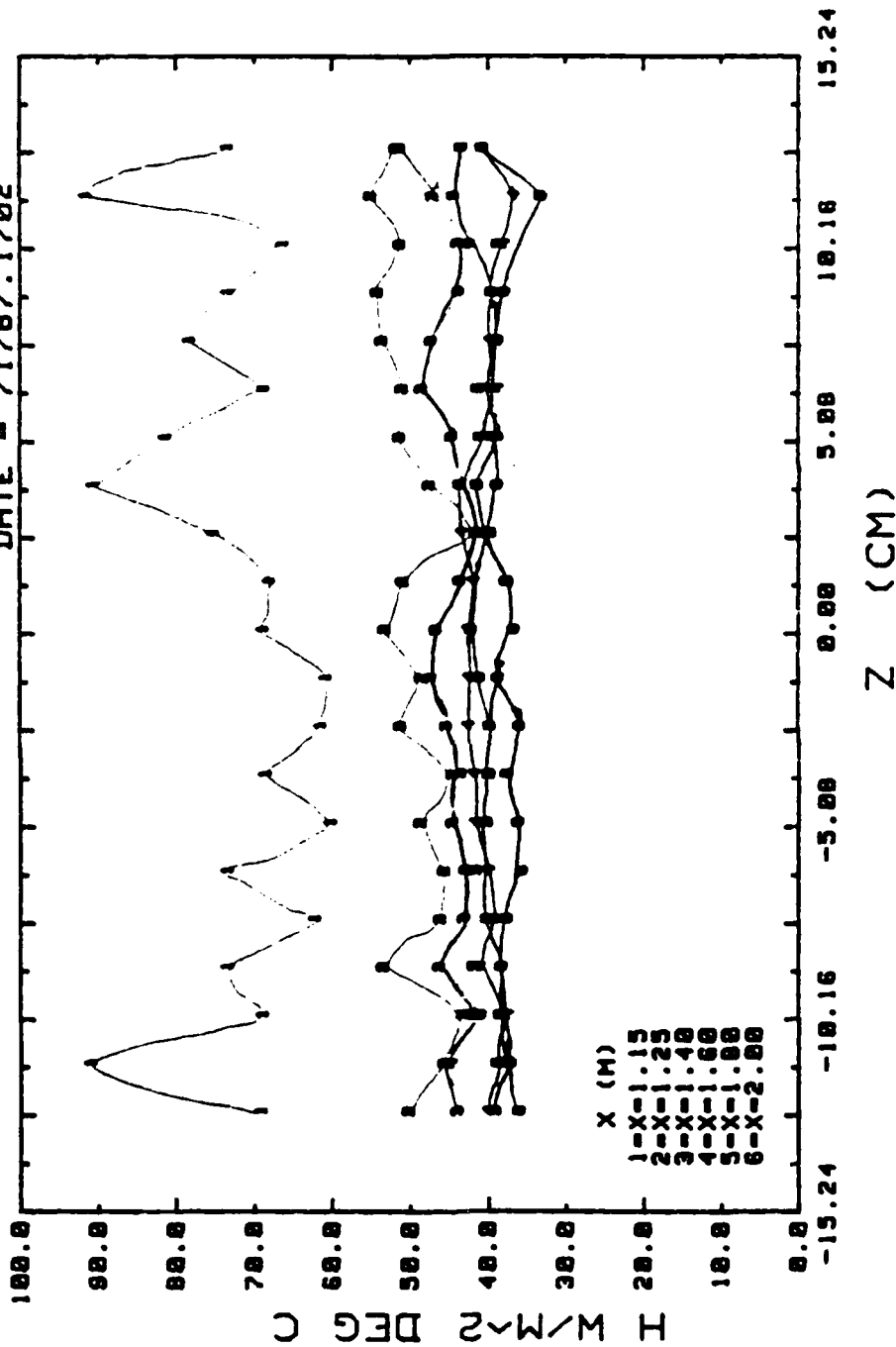


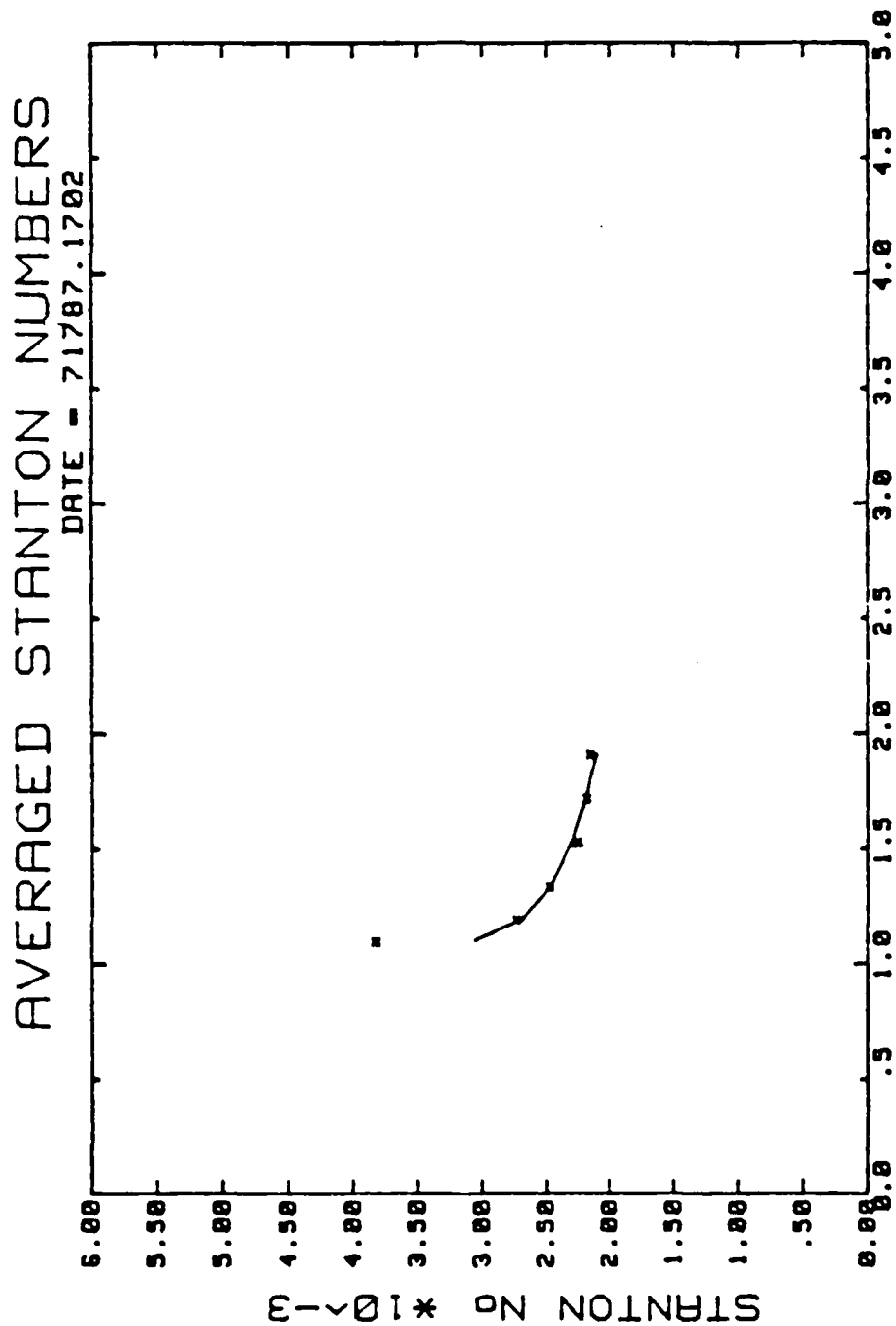
Fig. 11. BOUNDARY LAYER, 10 M/S NO FILM COOLING  
X=1.480 M, HEATED PLATE, NO VORTEX

# SPANWISE HEAT TRANSFER COEFFICIENT

DATE = 71787.1702



FREE STREAM 15 M/S, NO FILM COOLING  
Fig. 12. Spanwise Variation of Heat Transfer Coefficients.



REX \* 10<sup>6</sup>  
Fig. 13. FREESTREAM 15 M/S, NO FILM COOLING

# STANTON NUMBER RATIOS, VORTEX GEN #2

DATE = 72187.1524

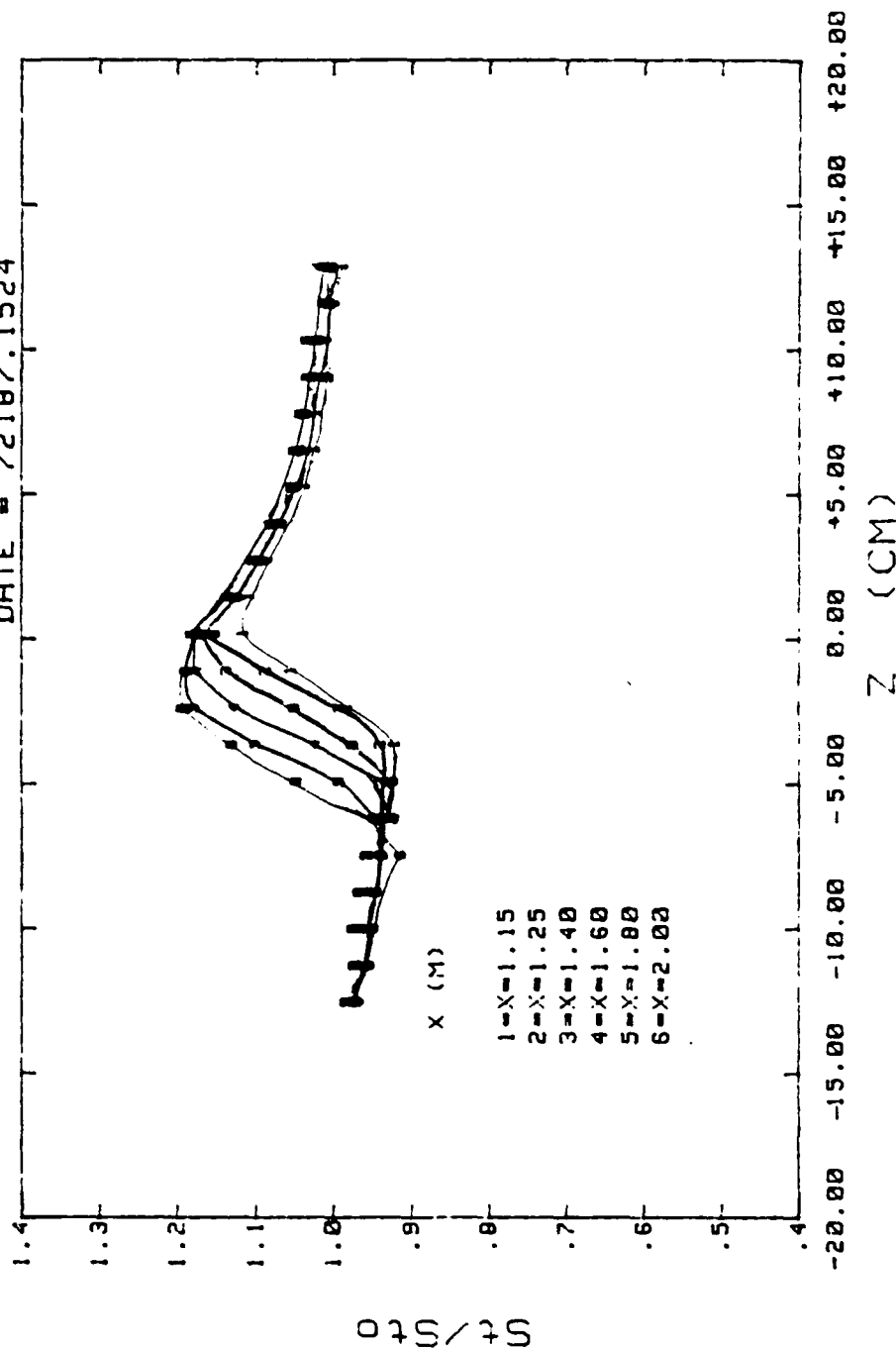


Fig. 14. FREE STREAM 10 M/S, NO FILM COOLING

DATE - 72187.11748

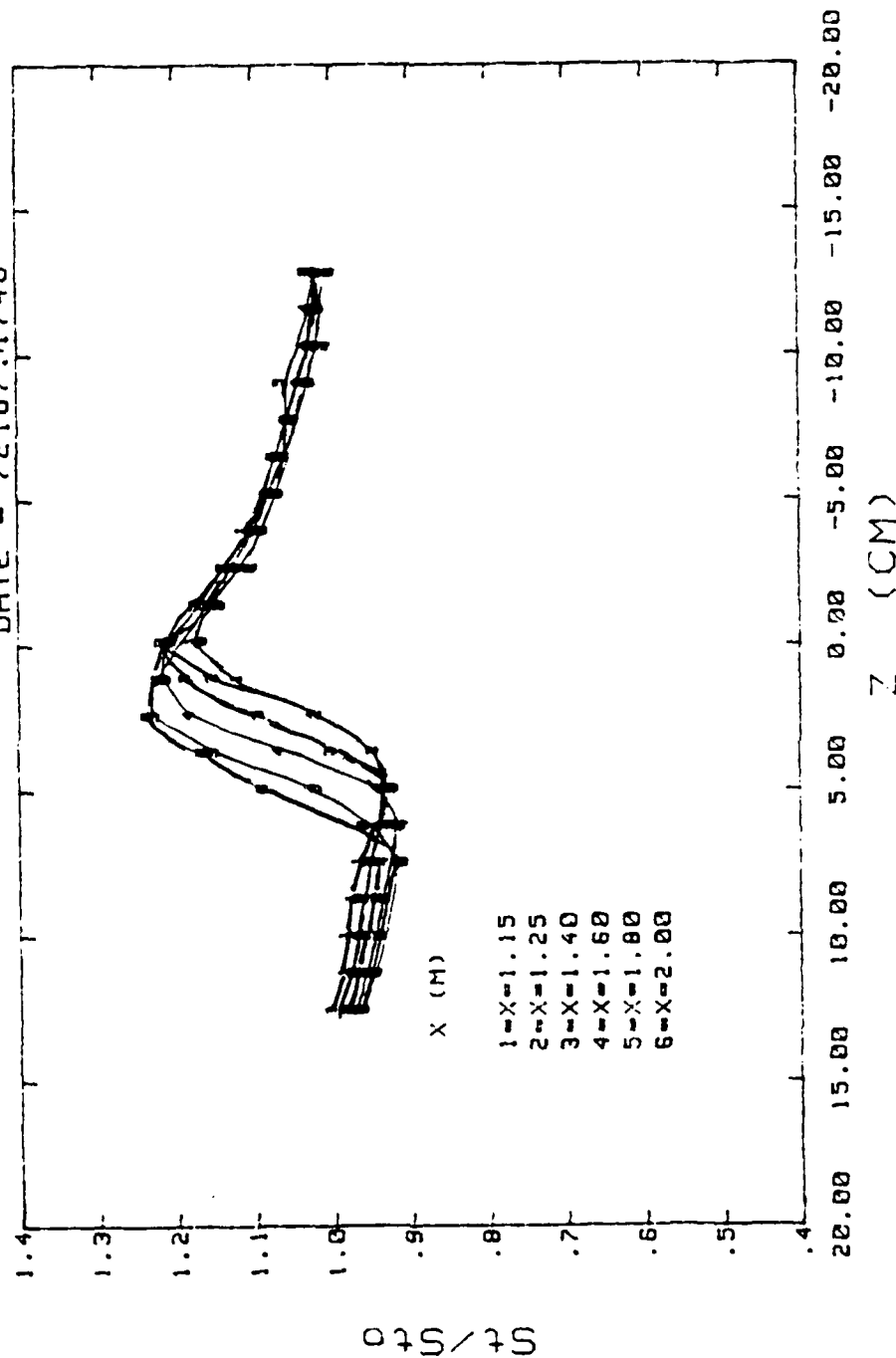


Fig. 15. FREE STREAM 15 M/S, NO FILM COOLING



# STANTON NUMBER RATIOS

DATE = 72487.1401

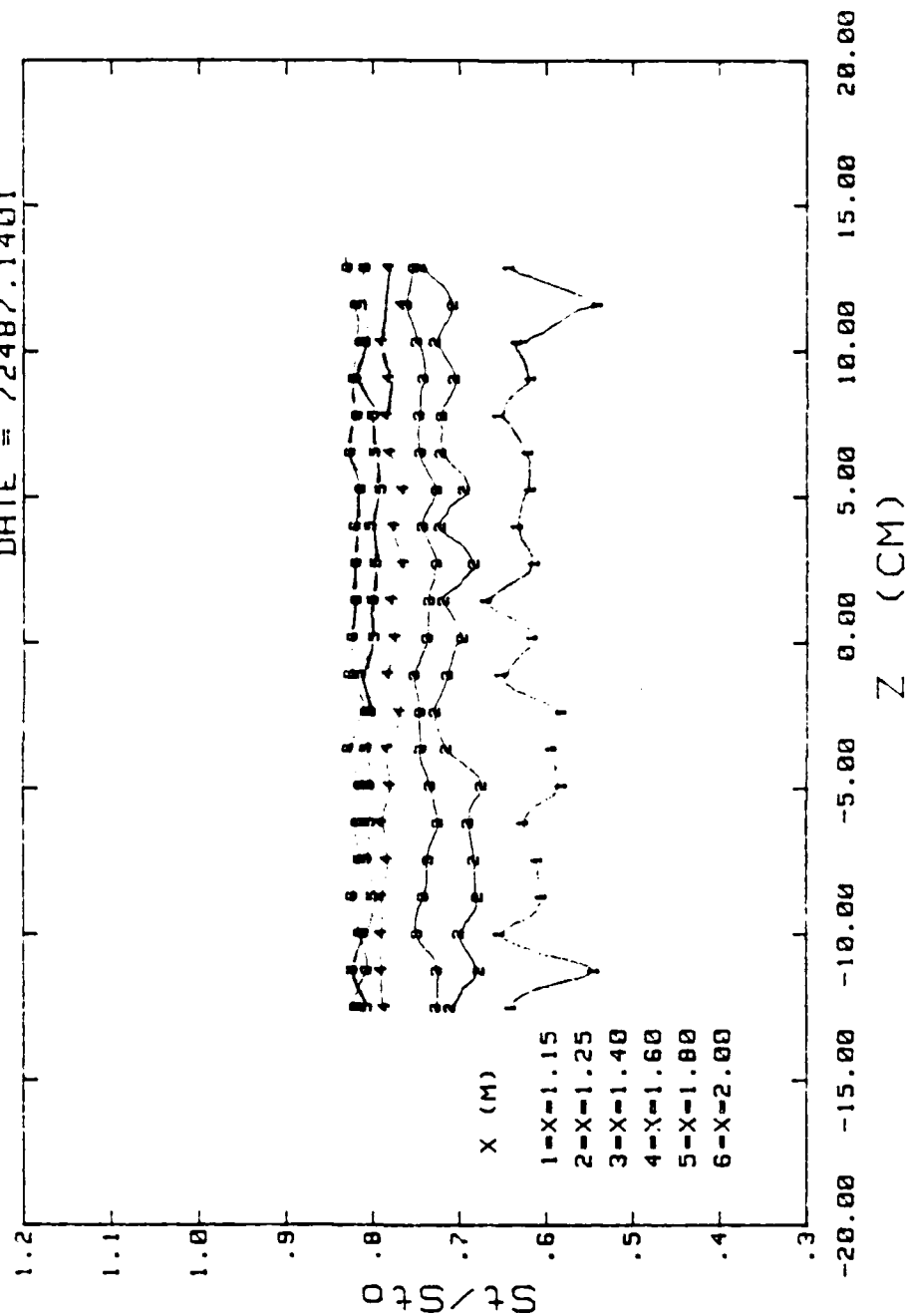


Fig. 16. FREE STREAM 10 M/S, WITH FILM COOLING

# STANTON NUMBER RATIOS

DATE - 80487.1412

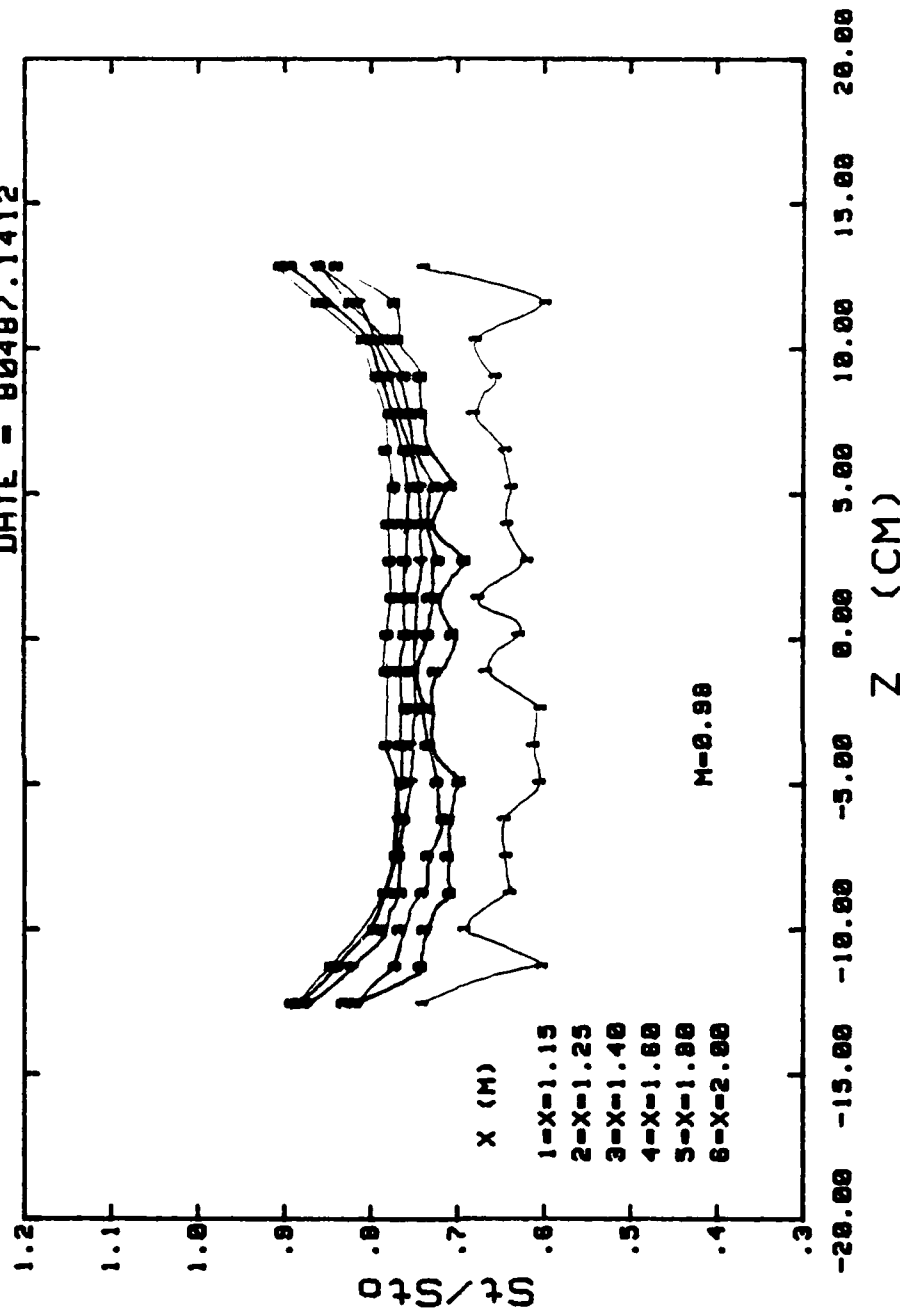


Fig. 17. FREE STREAM 10 M/S, WITH FILM COOLING

# STANTON NUMBER RATIOS

DATE = 72587.1451

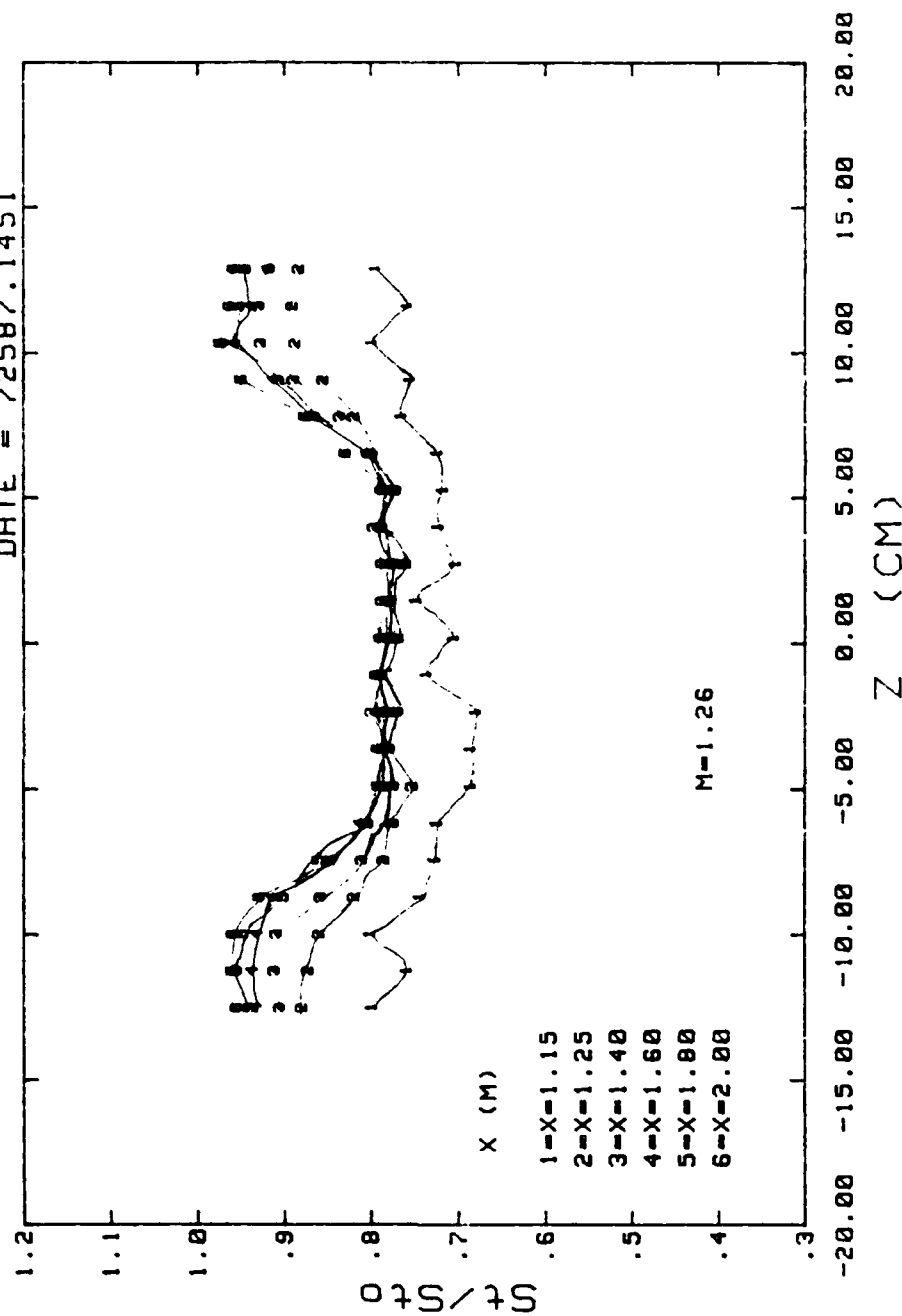


Fig. 18. FREE STREAM 10 M/S, WITH FILM COOLING

# STANTON NUMBER RATIOS

DATE = 72487.1621

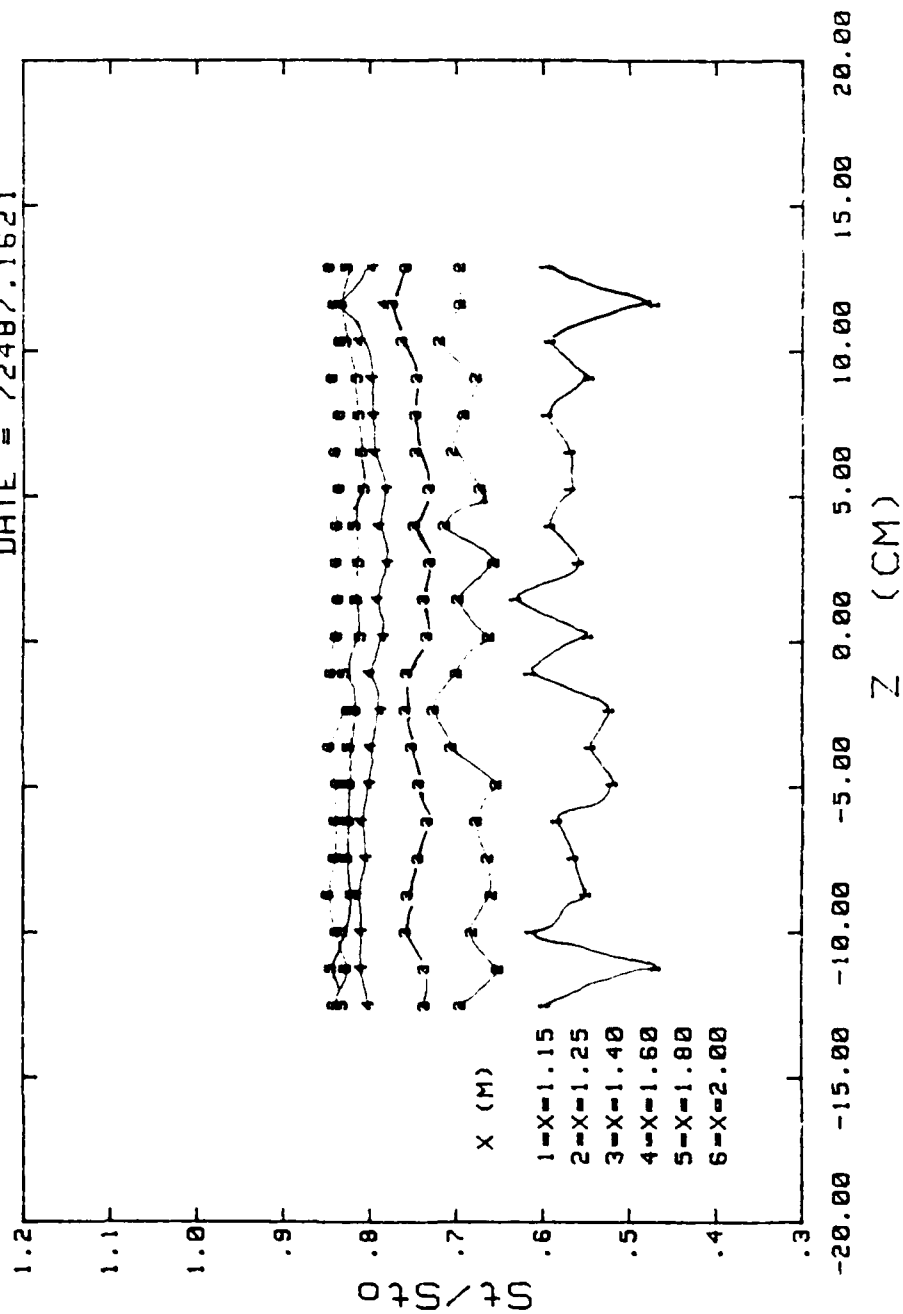


Fig. 19. FREE STREAM 15 M/S, WITH FILM COOLING

# STANTON NUMBER RATIOS

DATE = 72587.1808

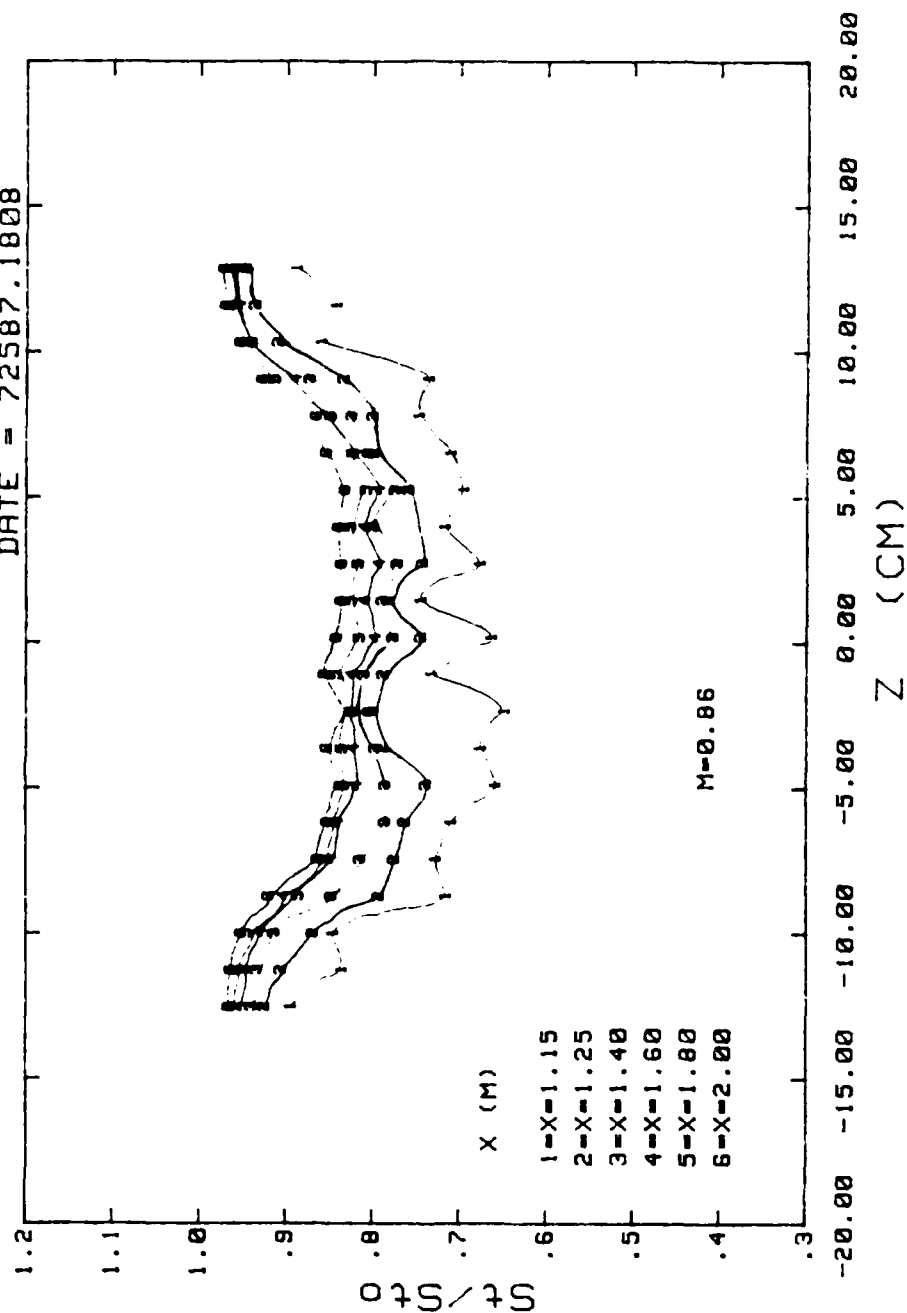
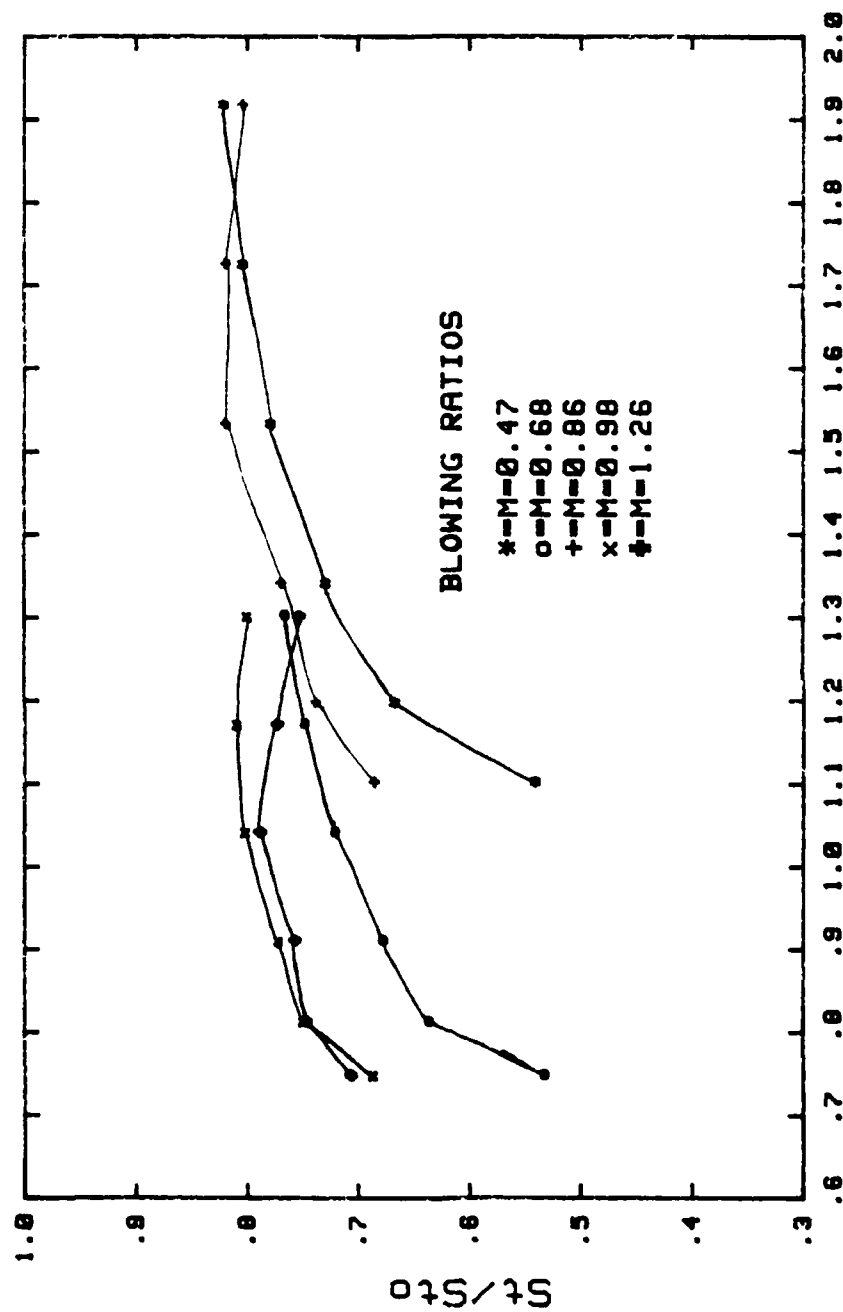


Fig. 20. FREE STREAM 15 M/S, WITH FILM COOLING

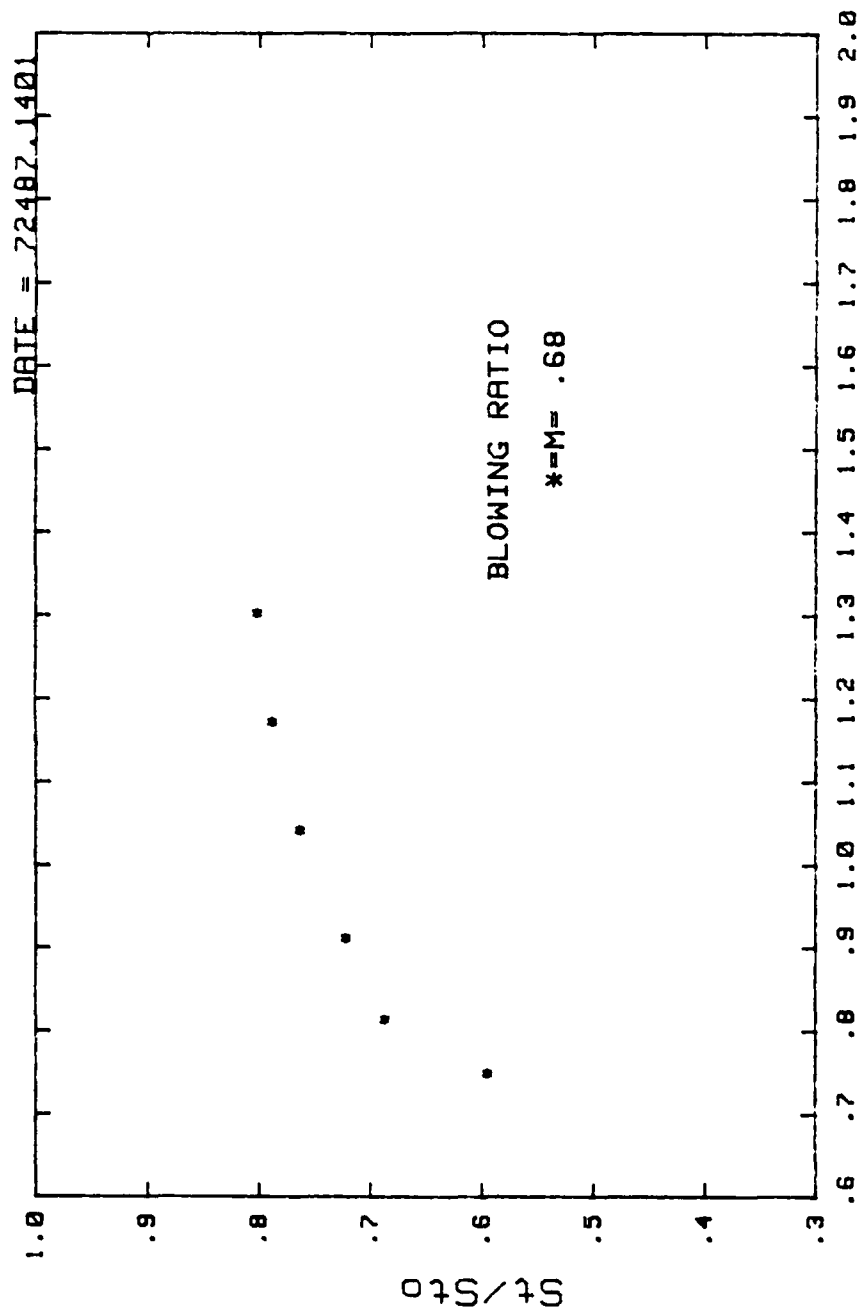
# FILM COOLING



REYNOLDS No  $\times 10^6$

Fig. 21. Averaged Stanton No. Ratios For Different Blowing Ratios.

# FILM COOLING



REYNOLDS No  $\times 10^6$

Fig. 22. FREE STREAM 10 M/S

# FILM COOLING

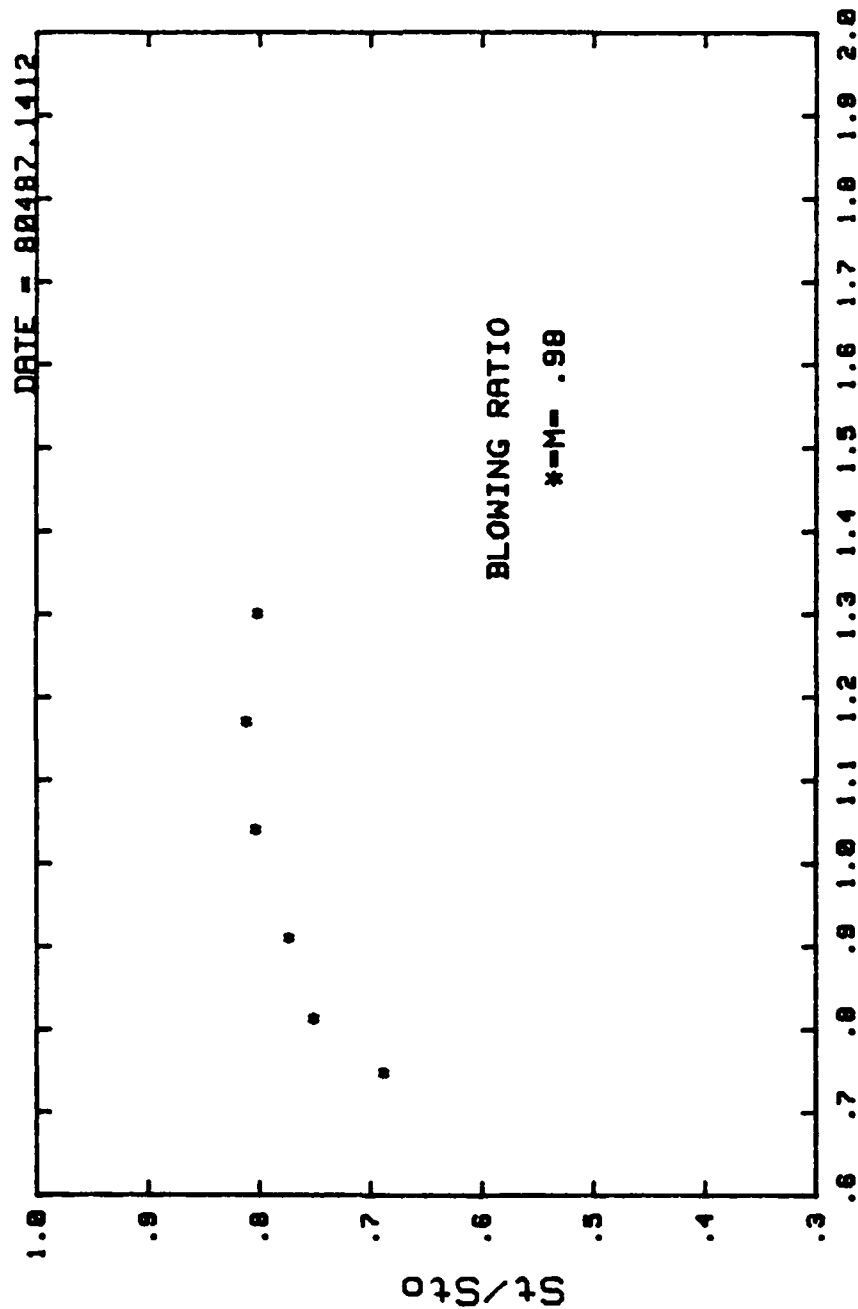
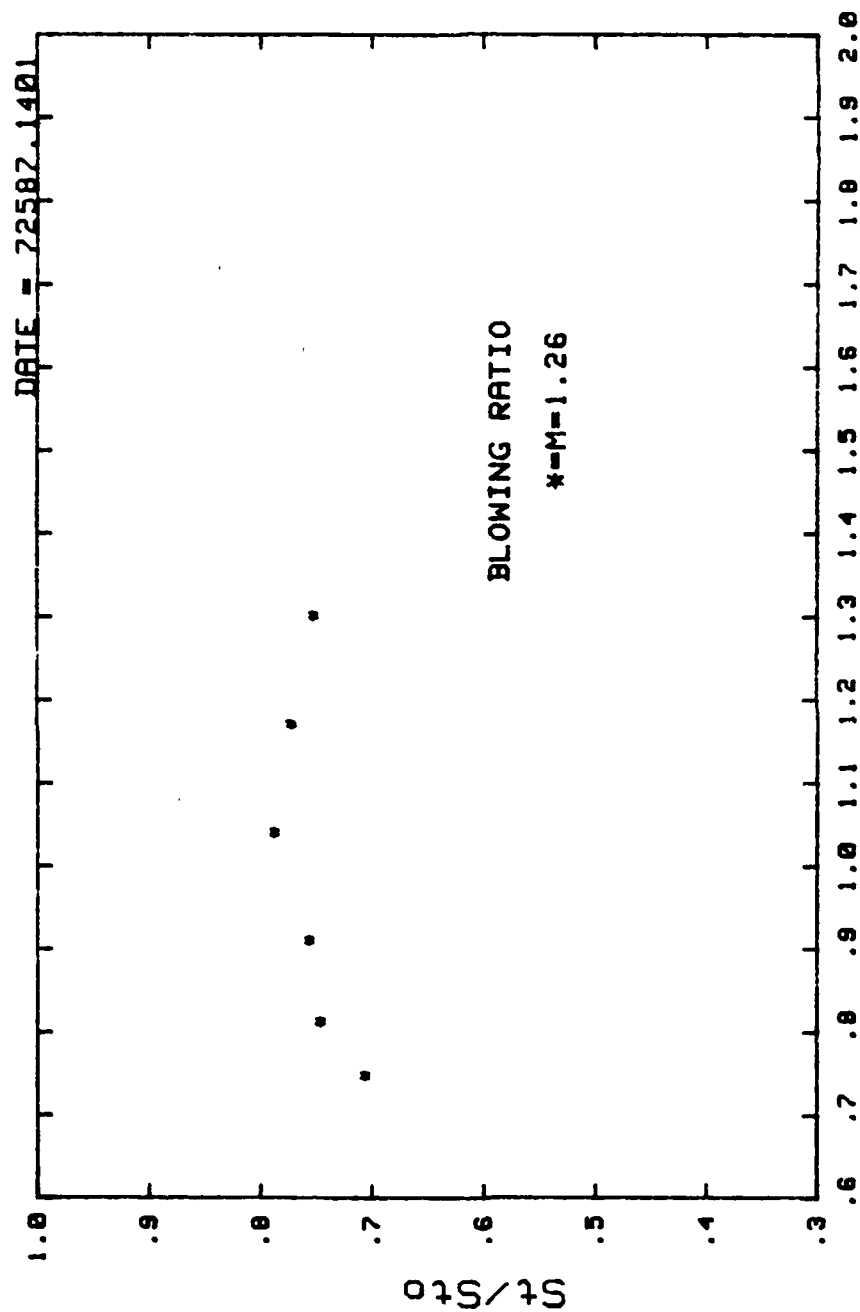


Fig. 23.

Fig. 23. FREE STREAM 10 M/S



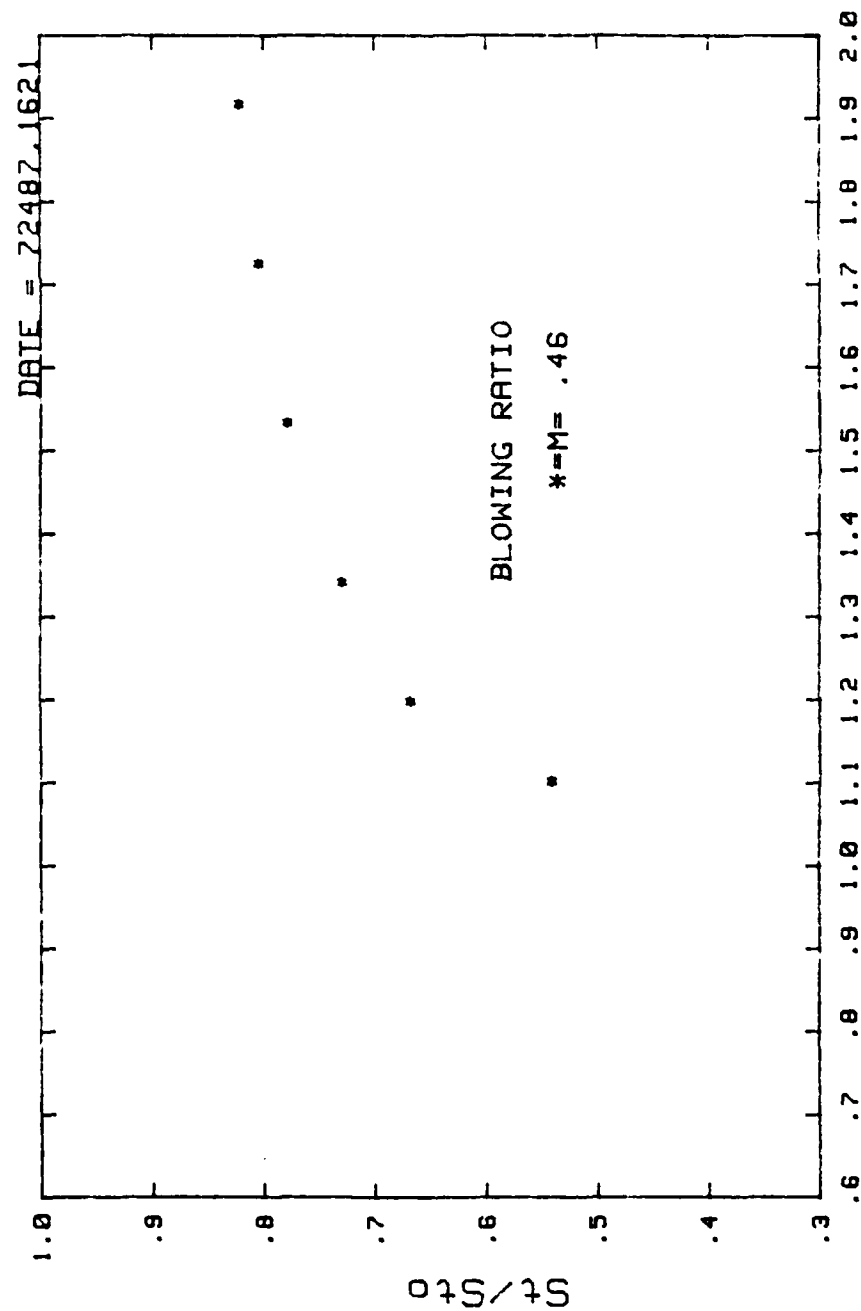
# FILM COOLING



REYNOLDS  $NO \times 10^6$

Fig. 24. FREE STREAM 10 M/S

# FILM COOLING



REYNOLDS No  $\times 10^{-6}$

Fig. 25. FREE STREAM 15 M/S

# FILM COOLING

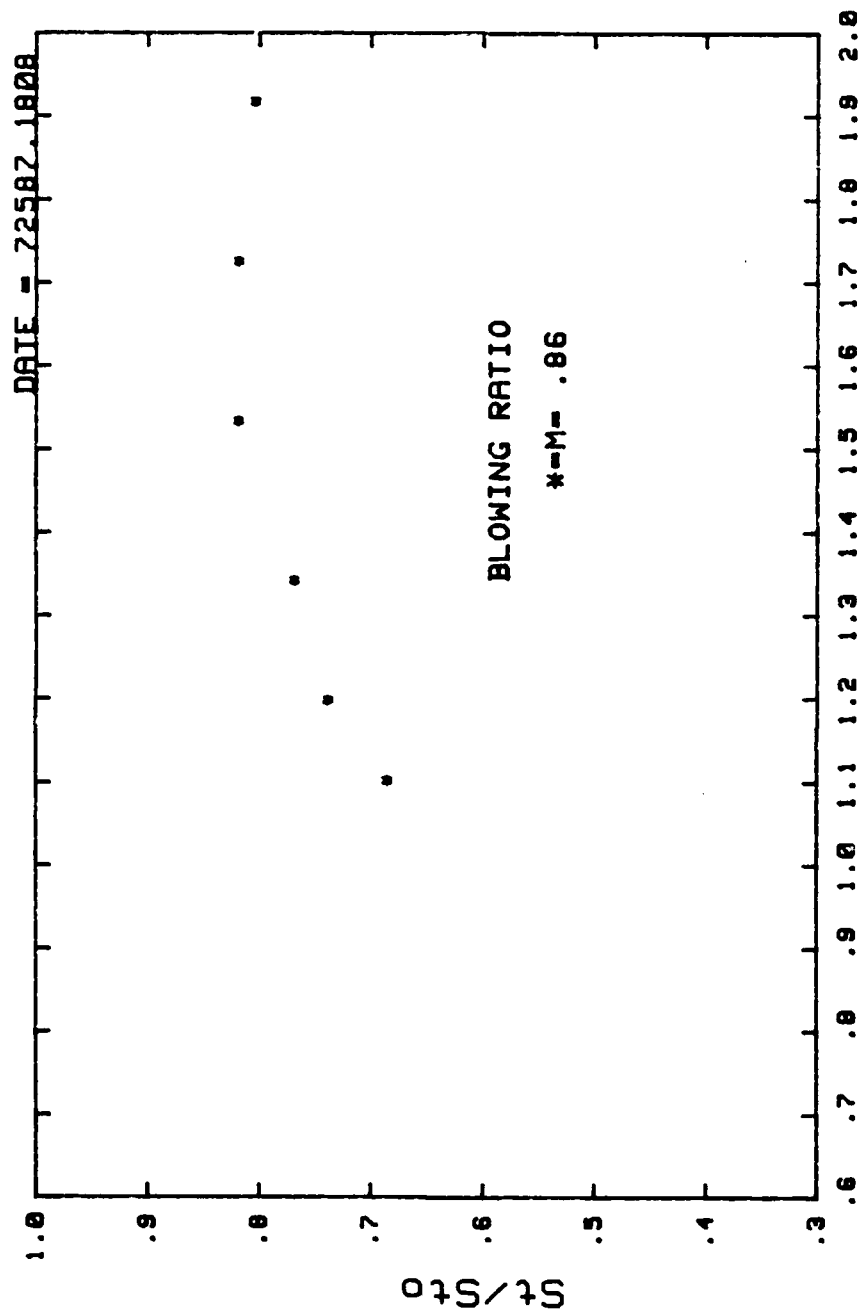


Fig. 26

# $St/St_0$ VS. BLOWING RATIO

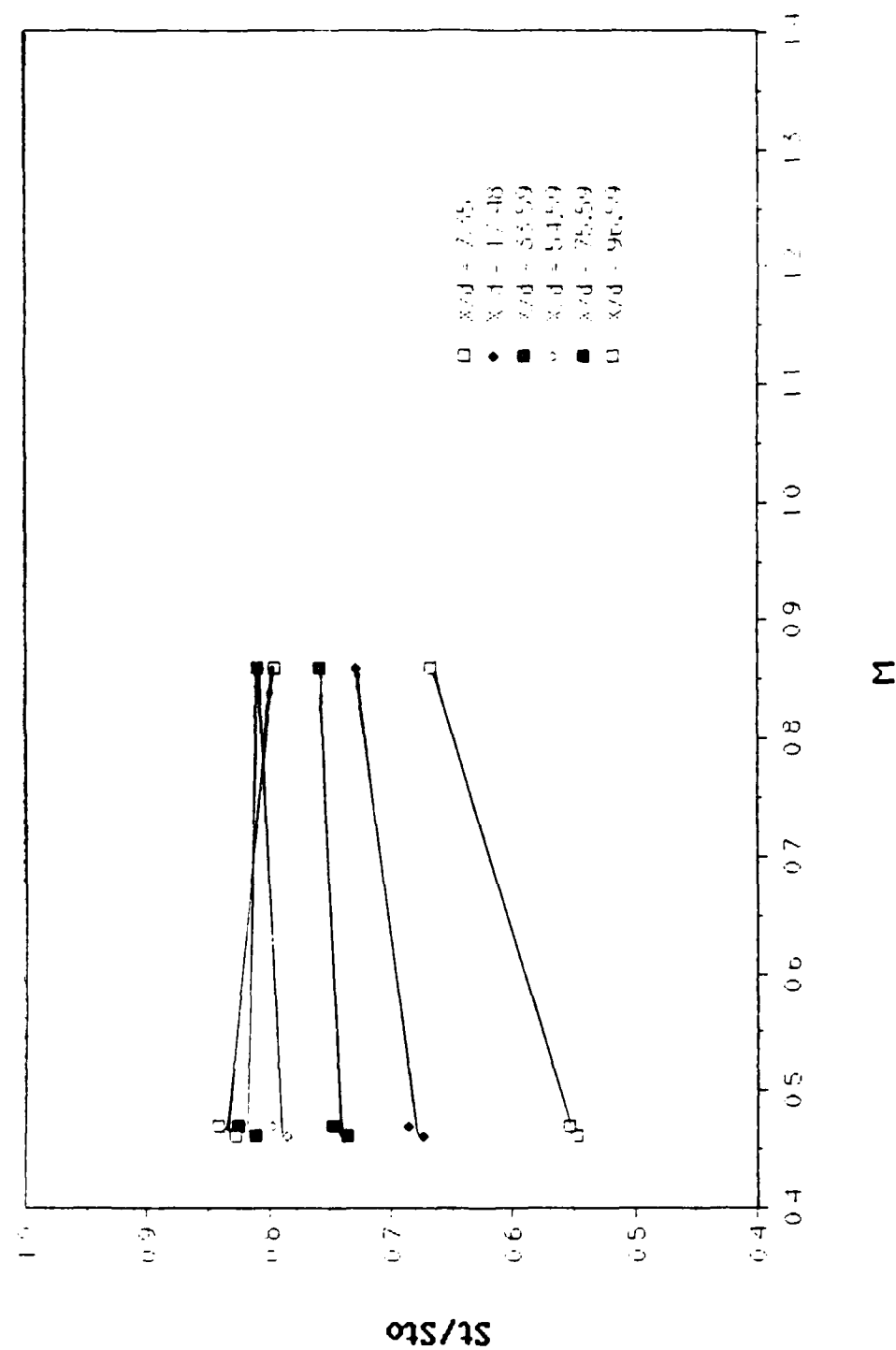


Fig. 27. Free Stream Velocity 15 m/s

# $St/St_0$ VS. BLOWING RATIO

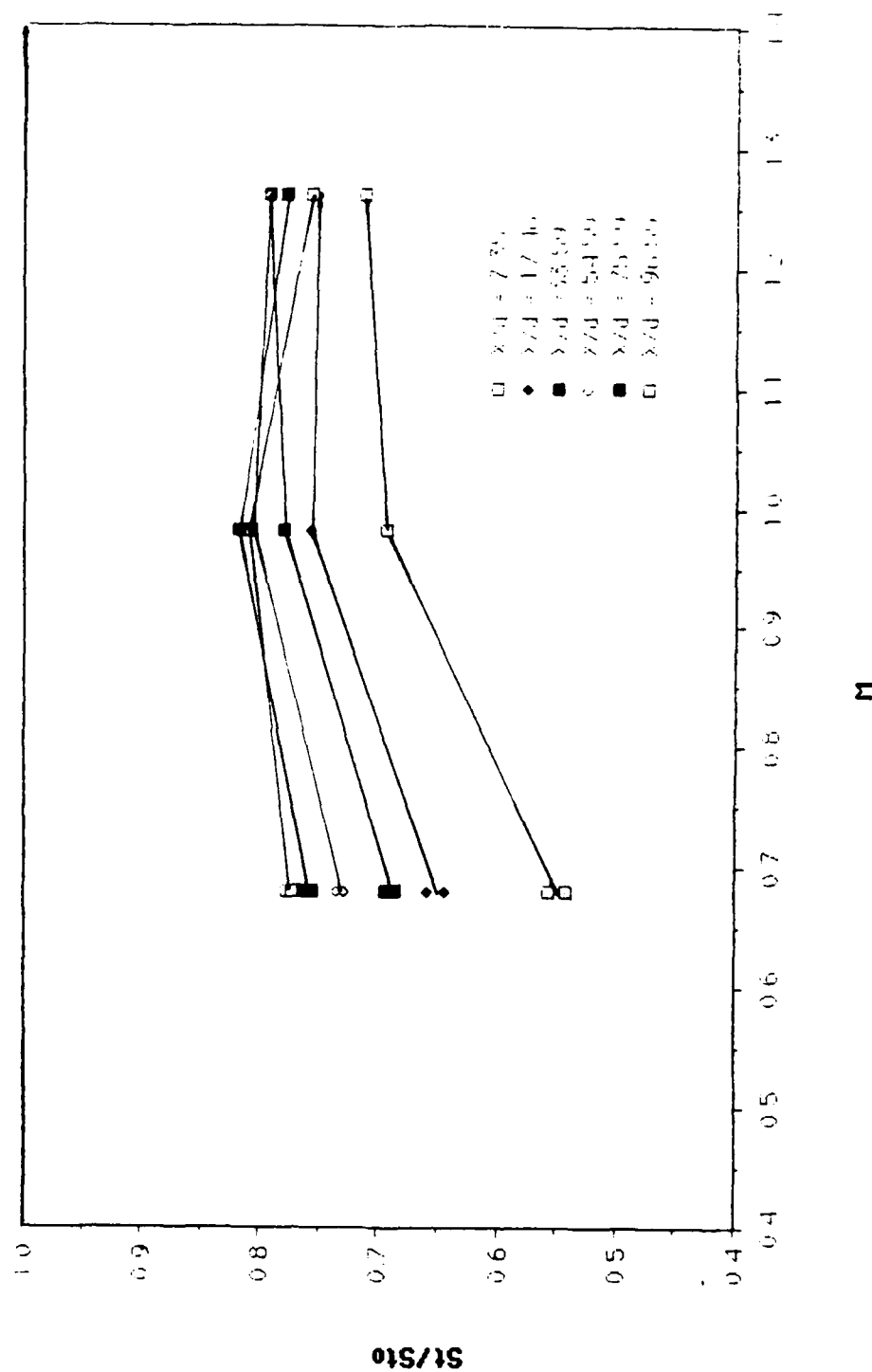
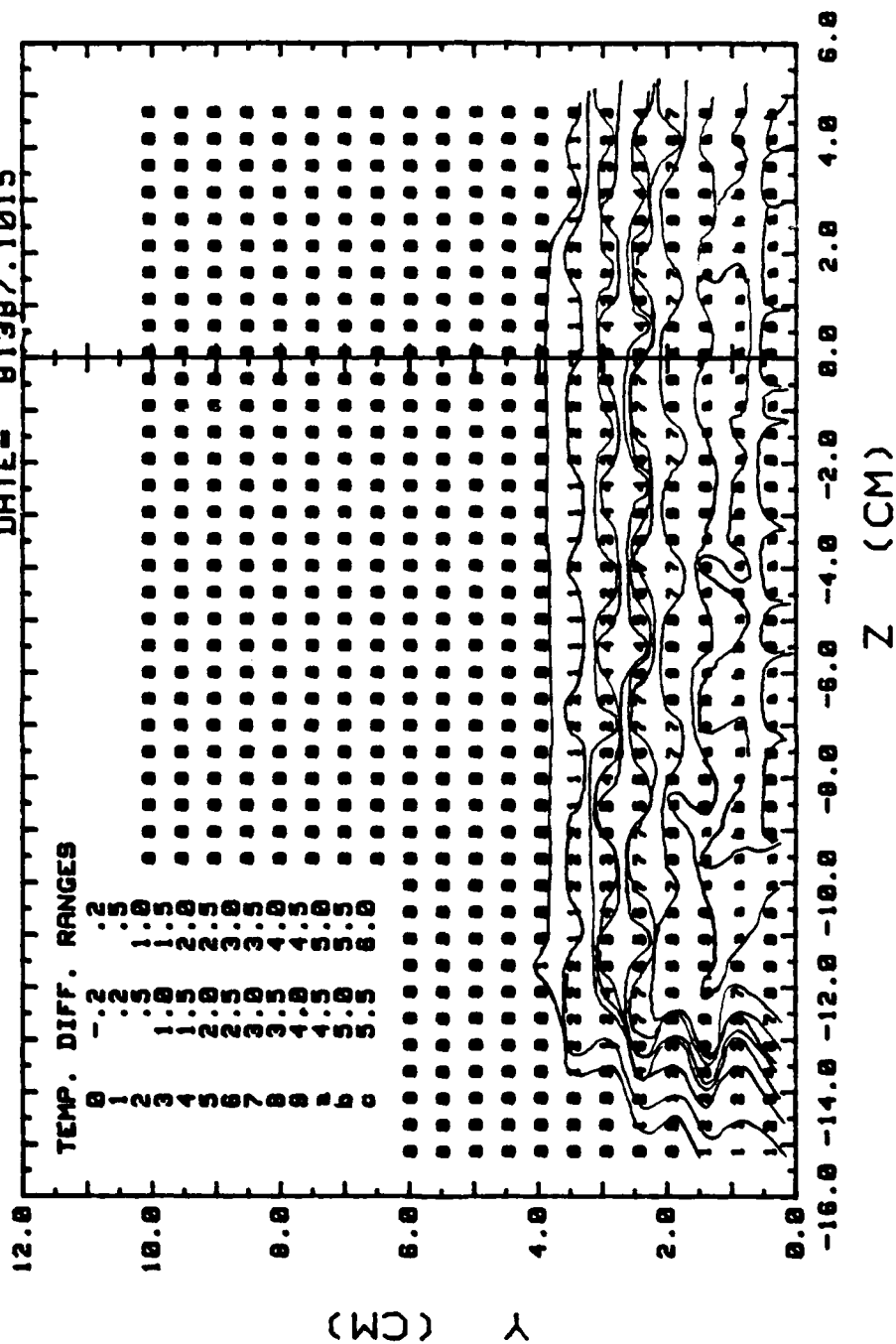


Fig. 28. Free Stream Velocity 10 m/s

# TEMPERATURE PROFILES

DATE- 81387.1015

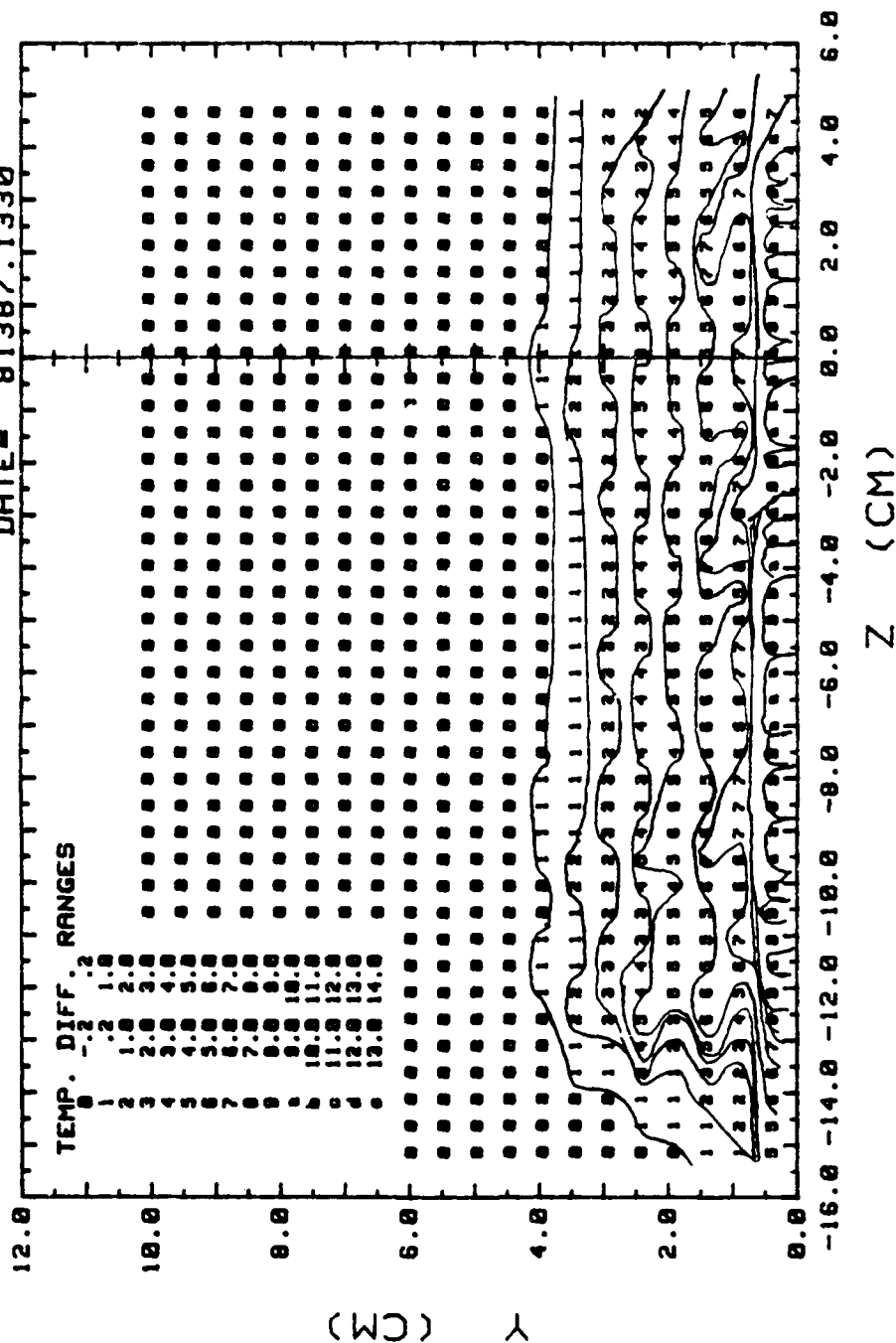


BOUNDARY LAYER, 10 M/S WITH FILM COOLING, M=0.98

Fig. 29. X=1.480 M, UNHEATED PLATE, NO VORTEX

# TEMPERATURE PROFILES

DATE= 81387.1330

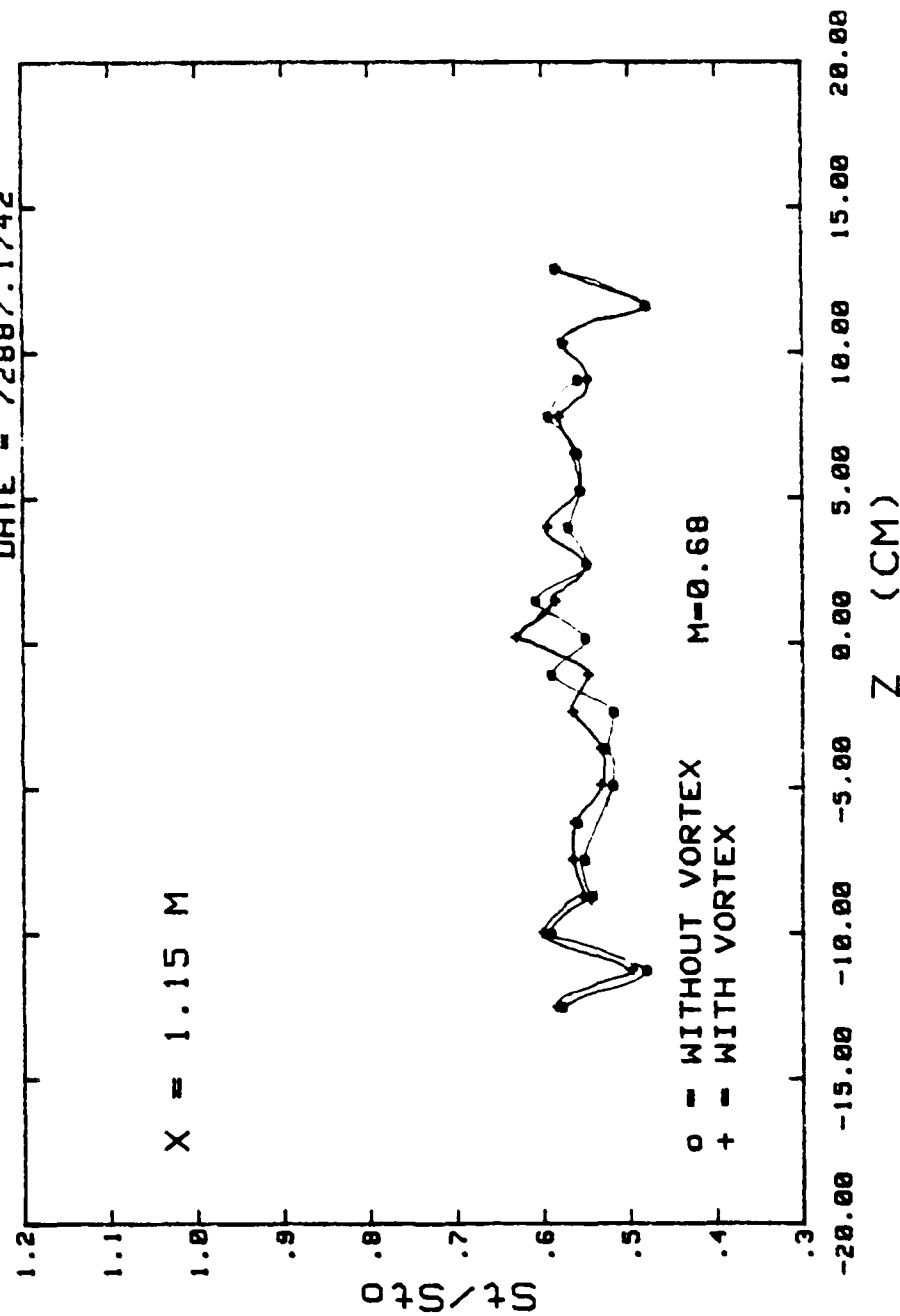


BOUNDARY LAYER, 10 M/S WITH FILM COOLING, M=0.98

Fig. 30. X=1.480 M, HEATED PLATE, NO VORTEX

# STANTON NUMBER RATIOS

DATE - 72887.1742



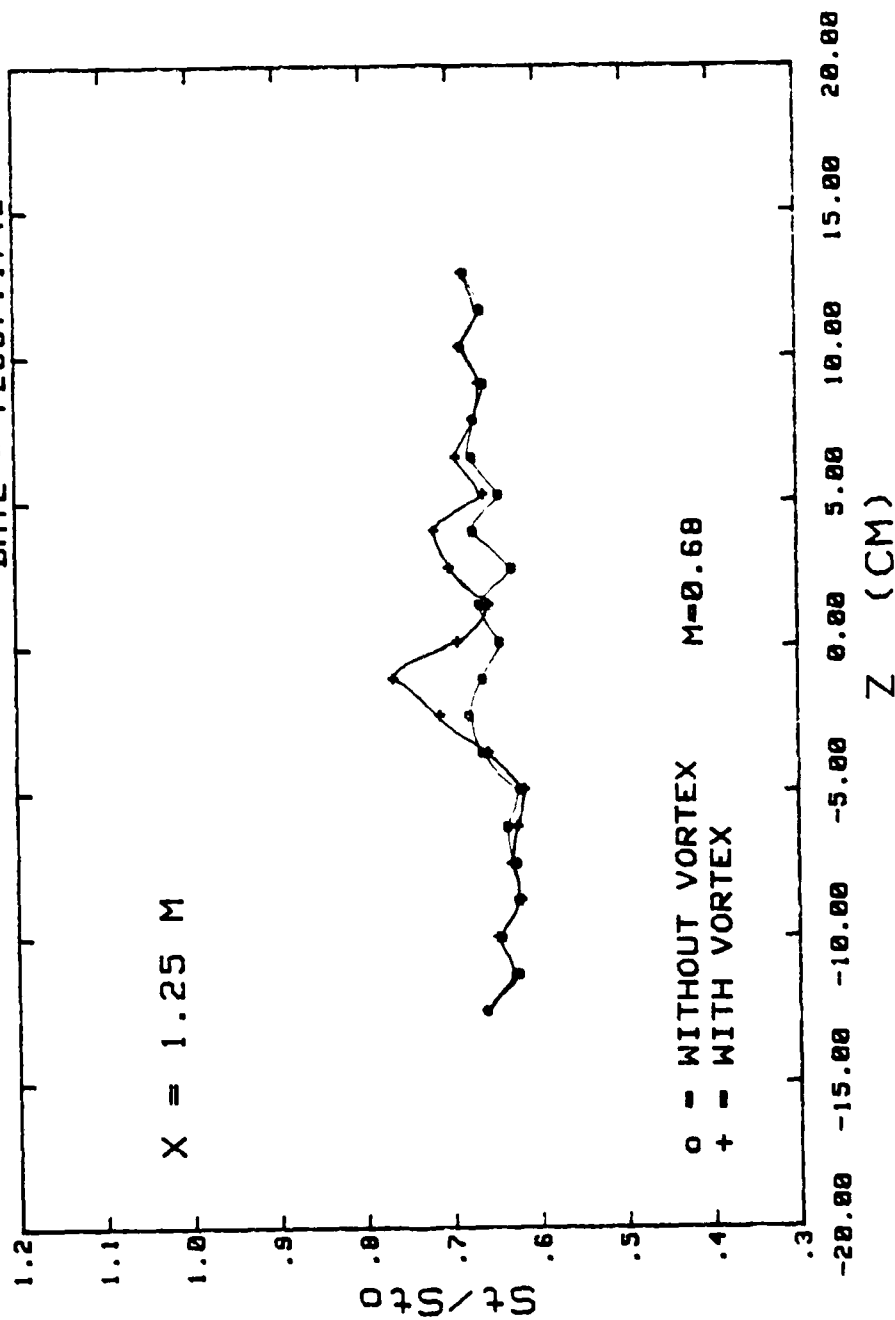
FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 3la. Spanwise Variation of Stanton Number Ratios.



# STANTON NUMBER RATIOS

DATE = 72887.1742

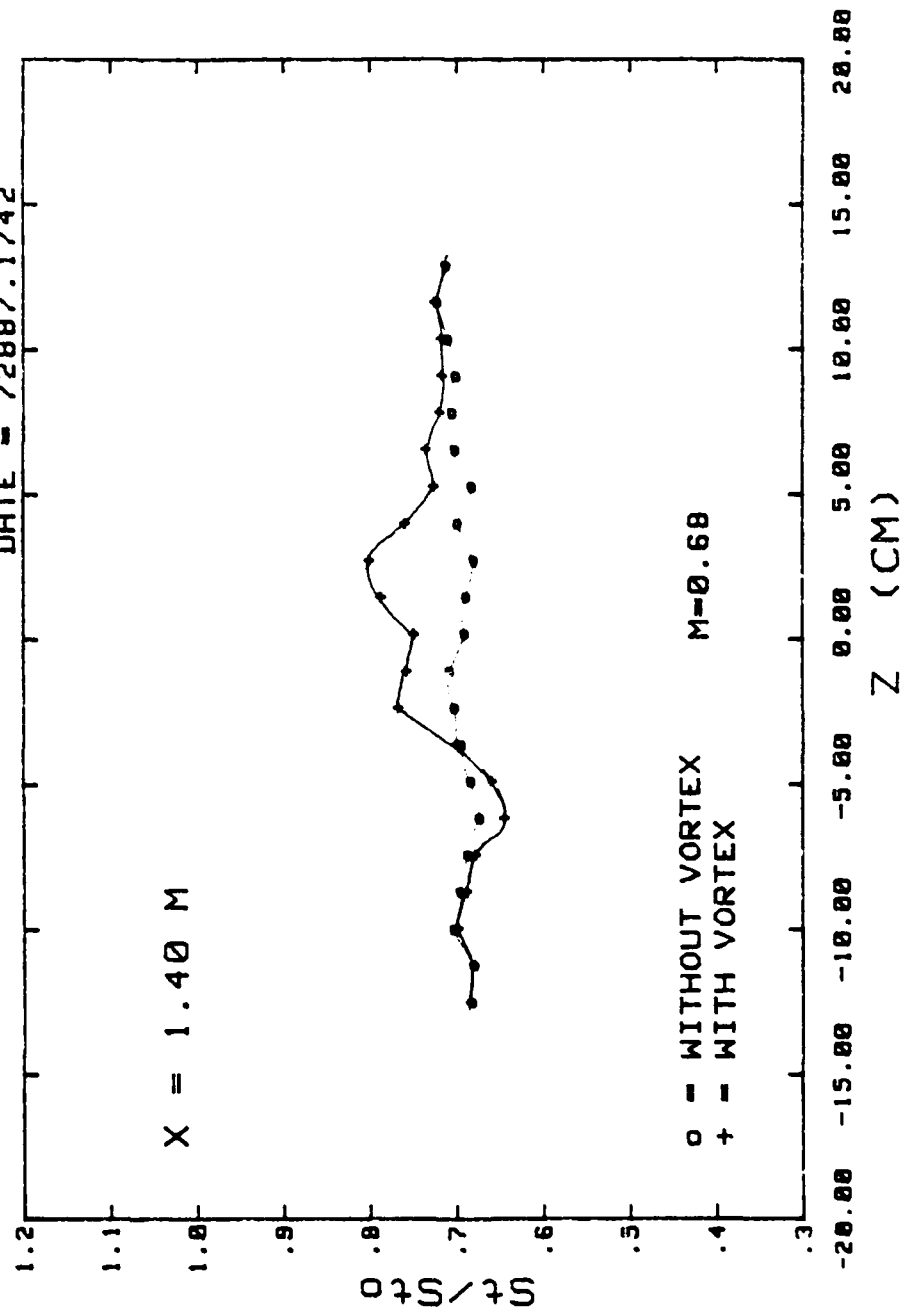


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 3lb. Spanwise Variation of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 72887.1742



FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Spanwise Variation of Stanton Number Ratios.

AD-A195 155

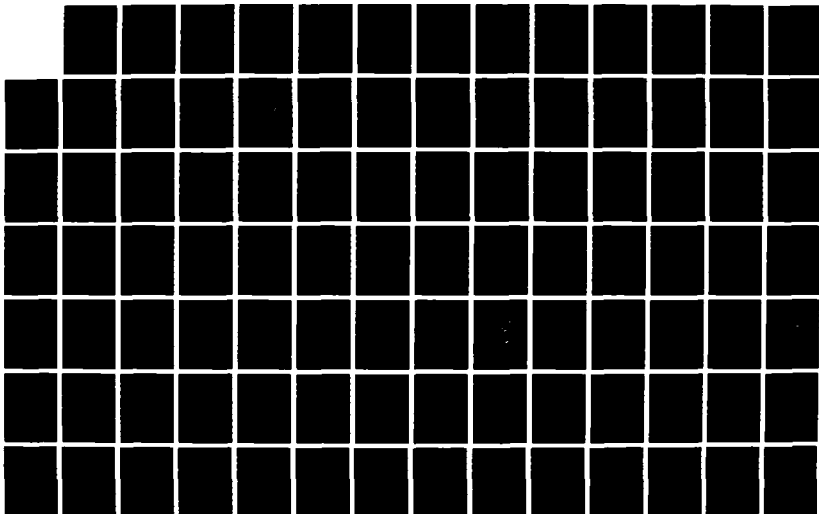
THE THERMAL BEHAVIOR OF FILM COOLED TURBULENT BOUNDARY  
LAYERS AS AFFECTED BY LONGITUDINAL VORTICES(U) NAVAL  
POSTGRADUATE SCHOOL MONTEREY CA A ORTIZ SEP 87

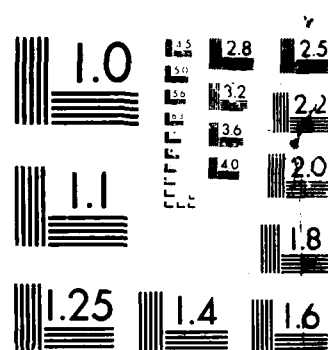
2/3

UNCLASSIFIED

F/G 20/13

NL

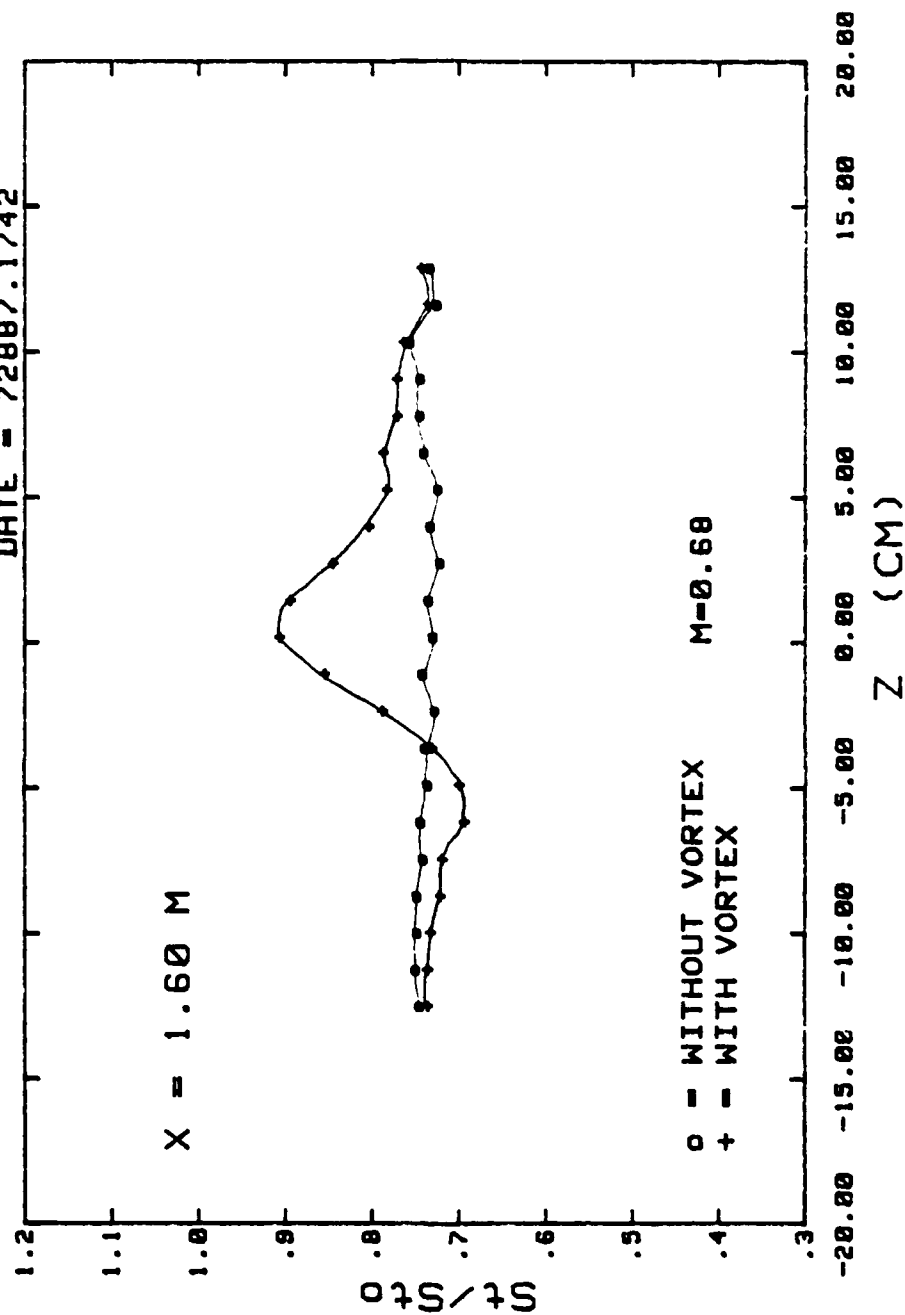




MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

# STANTON NUMBER RATIOS

DATE = 72887.1742

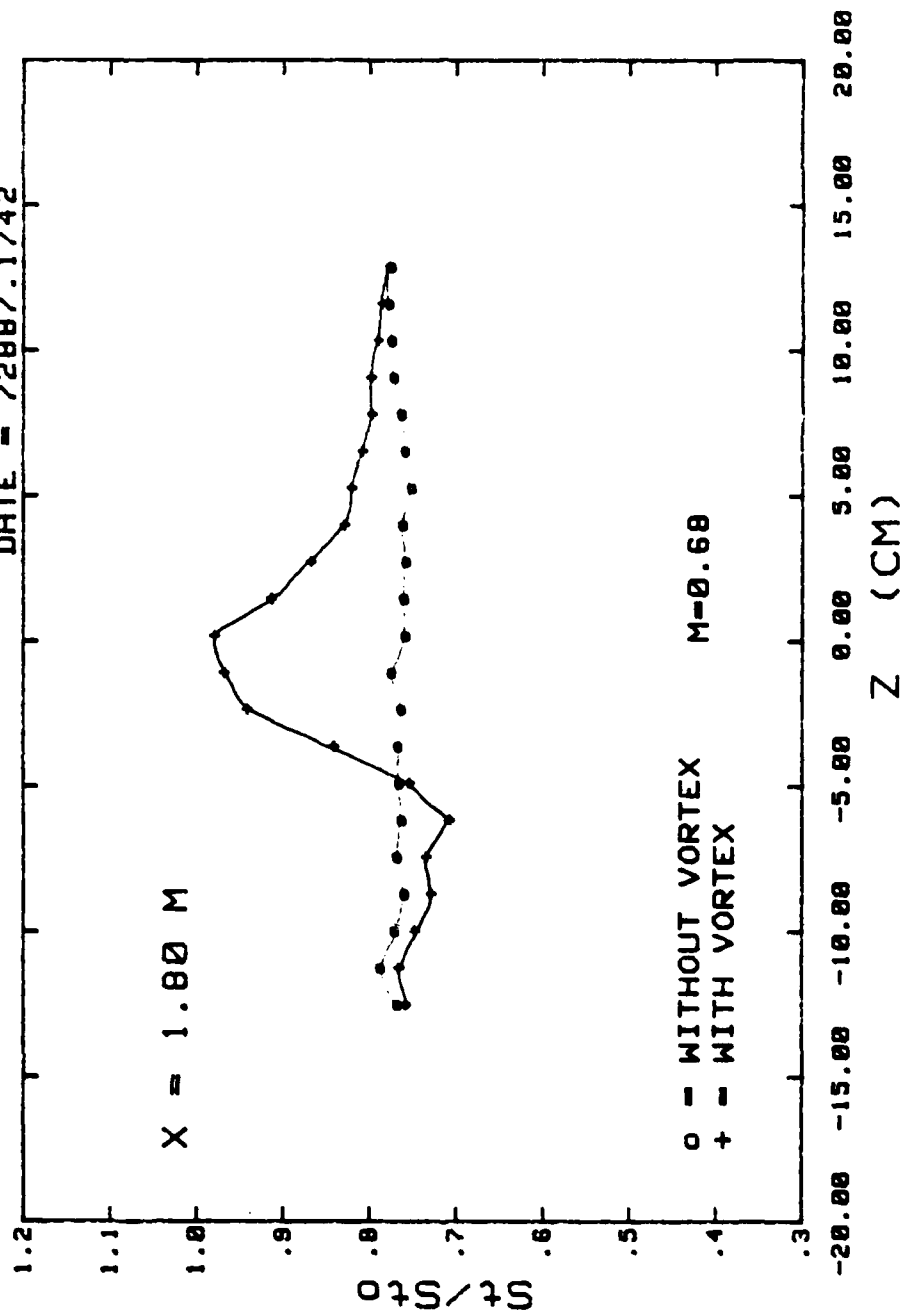


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 3ld. Spanwise Variation of Stanton Number Ratios.

# STANTON NUMBER RATIOS

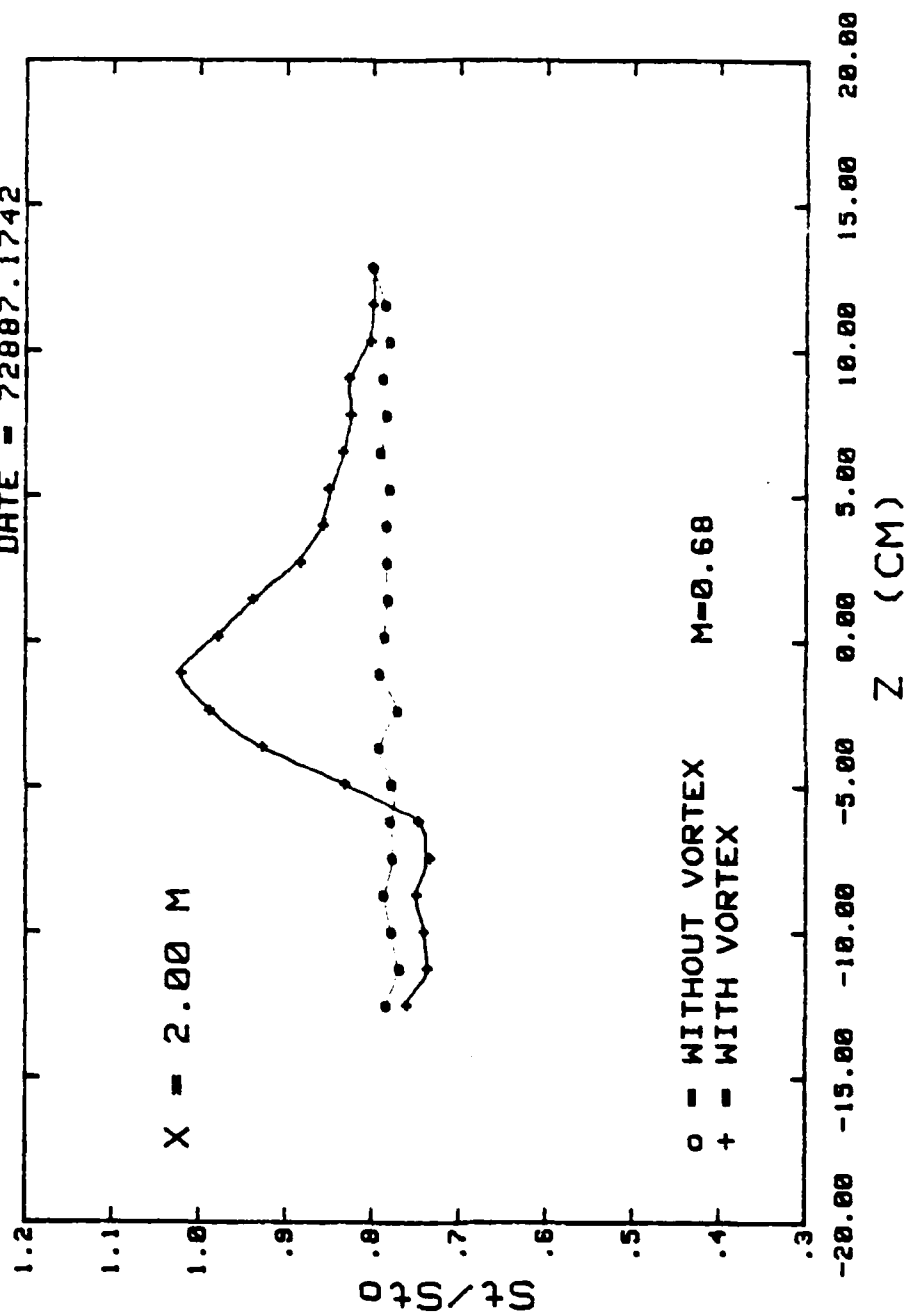
DATE = 72887.1742



FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm  
 Fig. 3le. Spanwise Variation of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 72087.1742

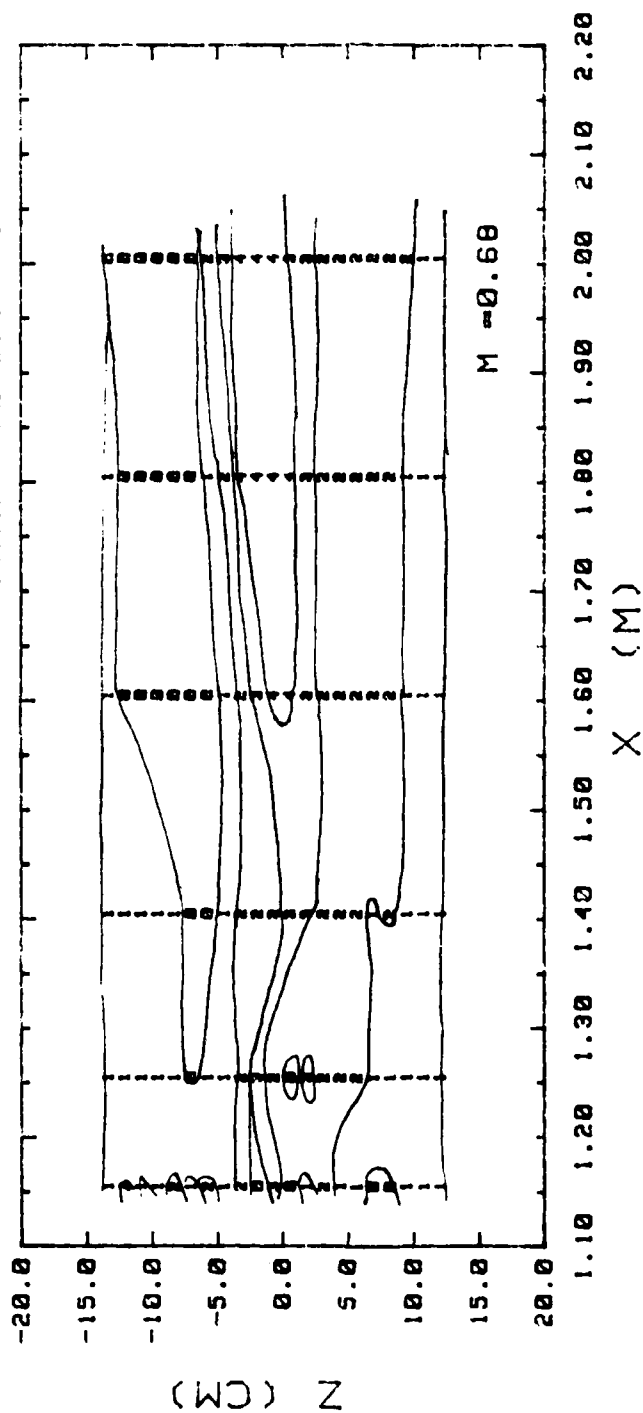


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 31f. Spanwise Variation of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 72087.1742



St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

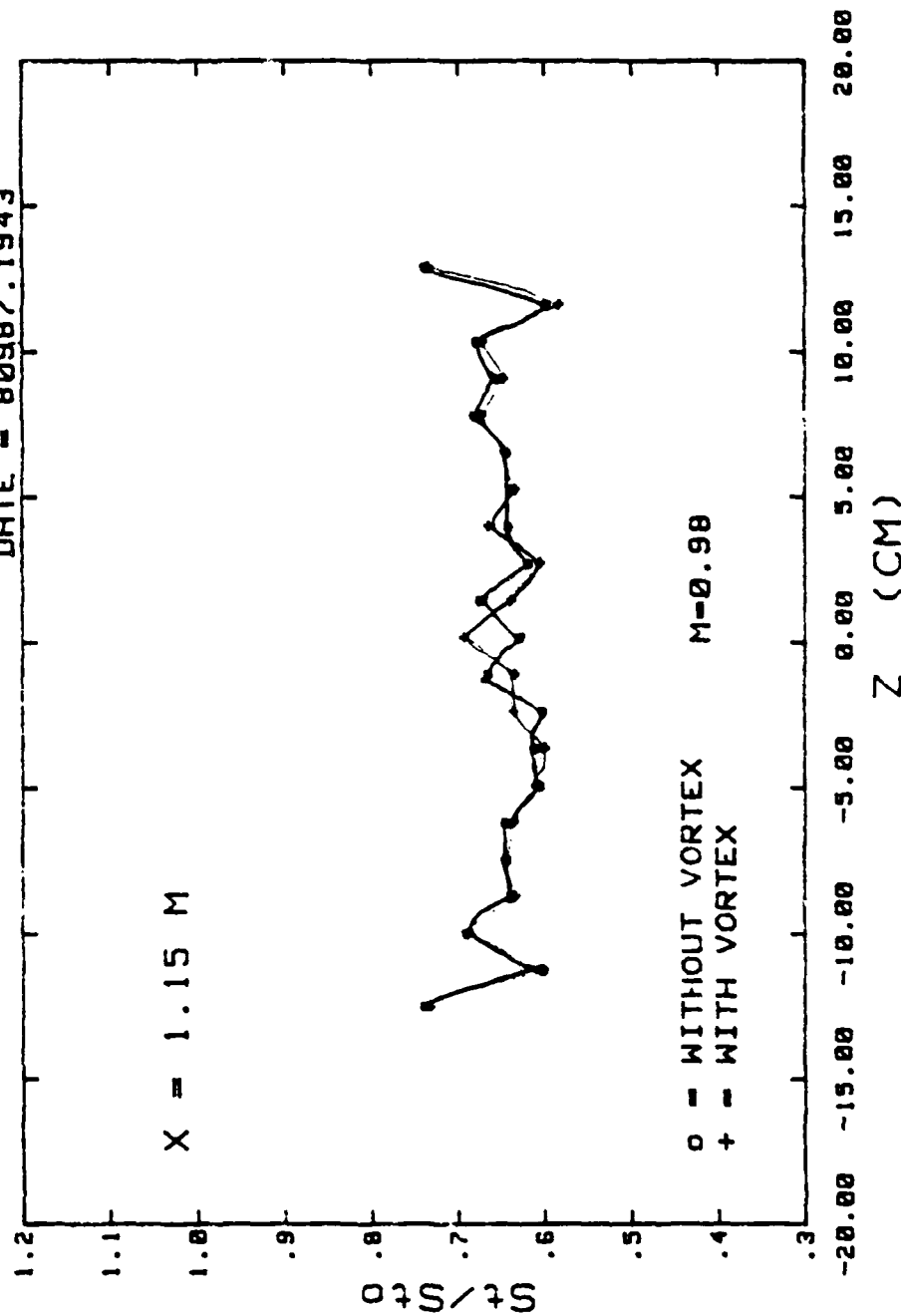
FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 4.79 cm

Fig. 32. Surface Contours.



# STANTON NUMBER RATIOS

DATE - 80987.1943

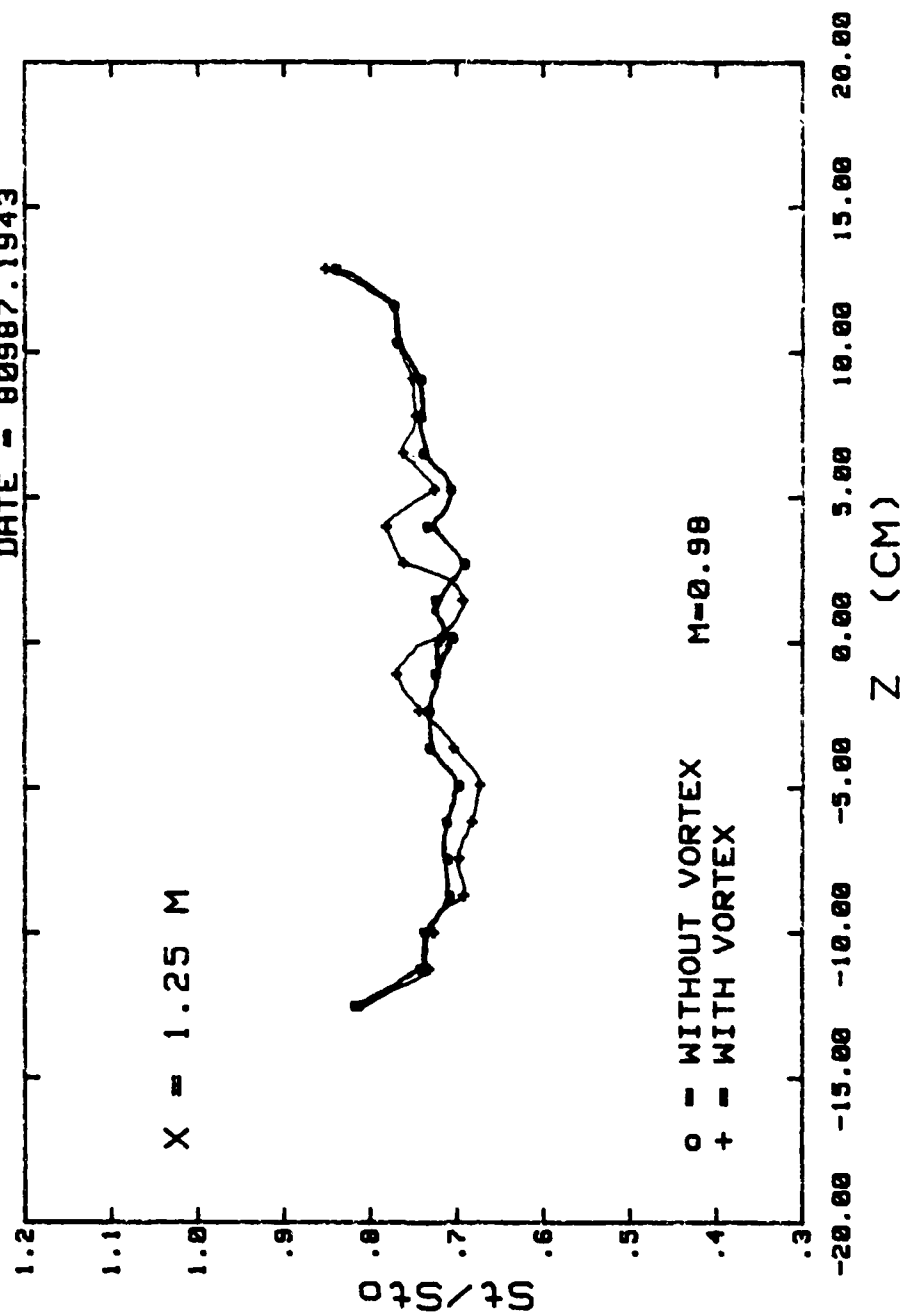


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 4.79 cm

Fig. 33a. Spanwise Variation of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 00987.1943

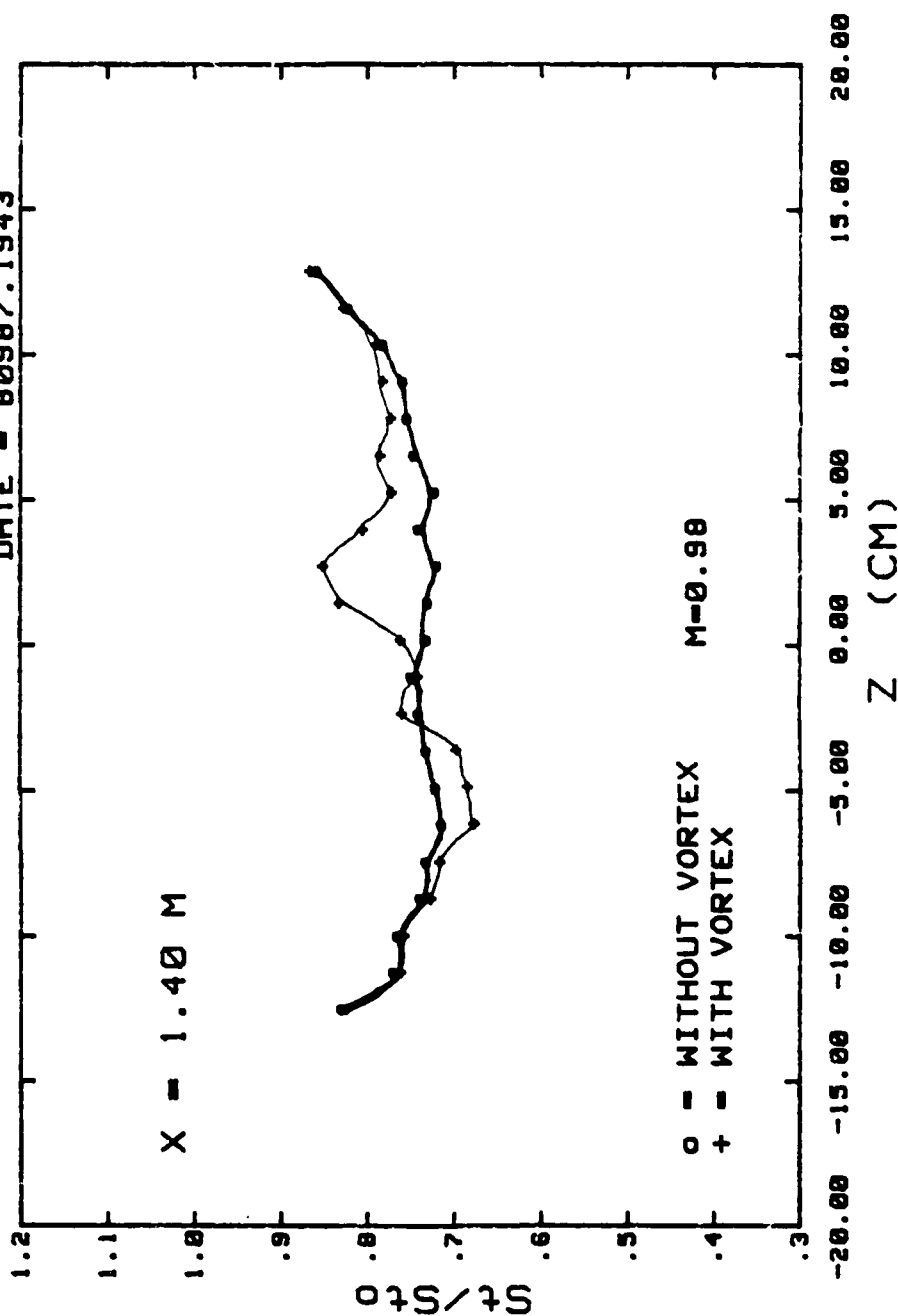


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 4.79 cm

Fig. 33b. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80987.1943

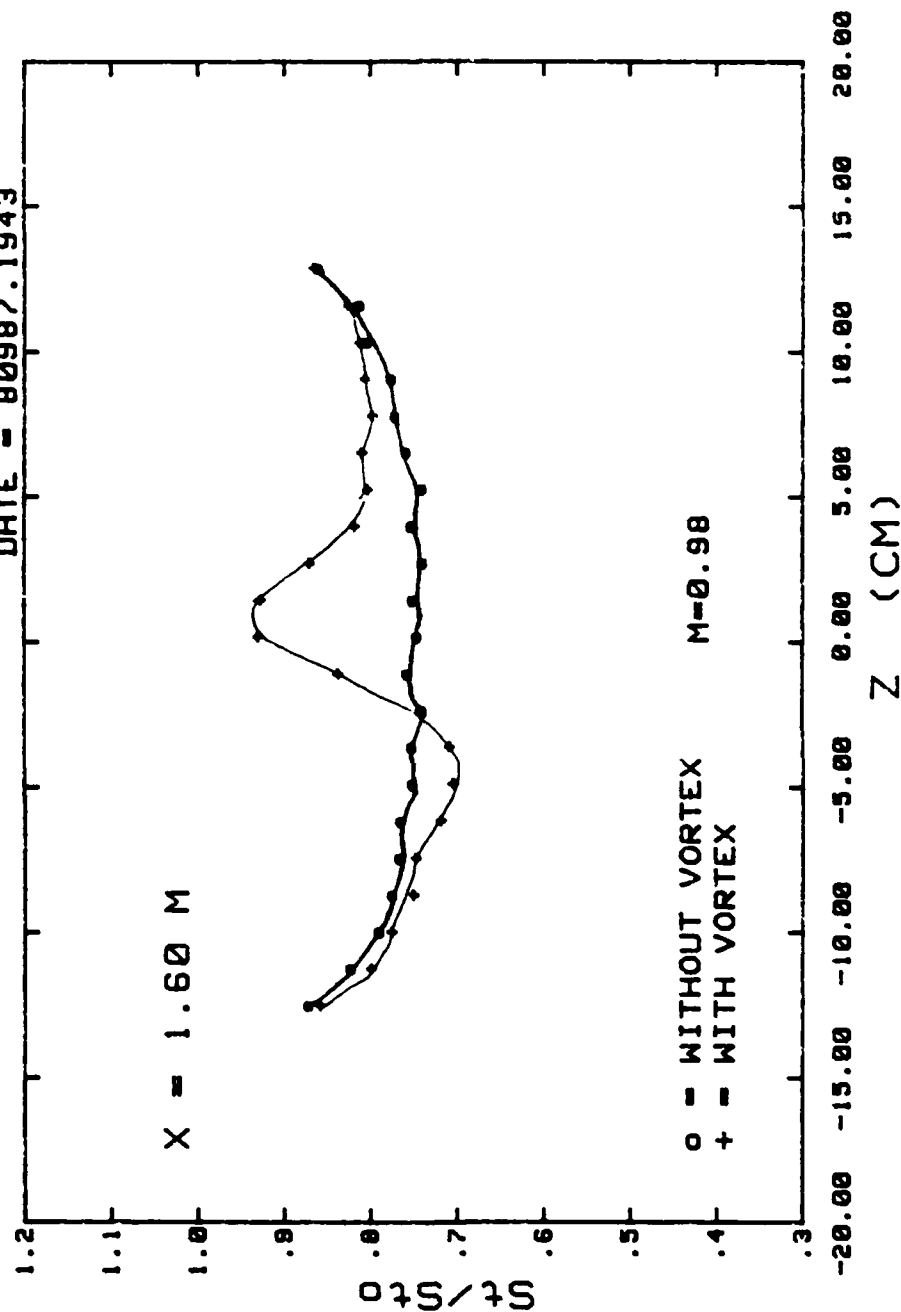


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 4.79 cm

Fig. 33c. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 80987.1943

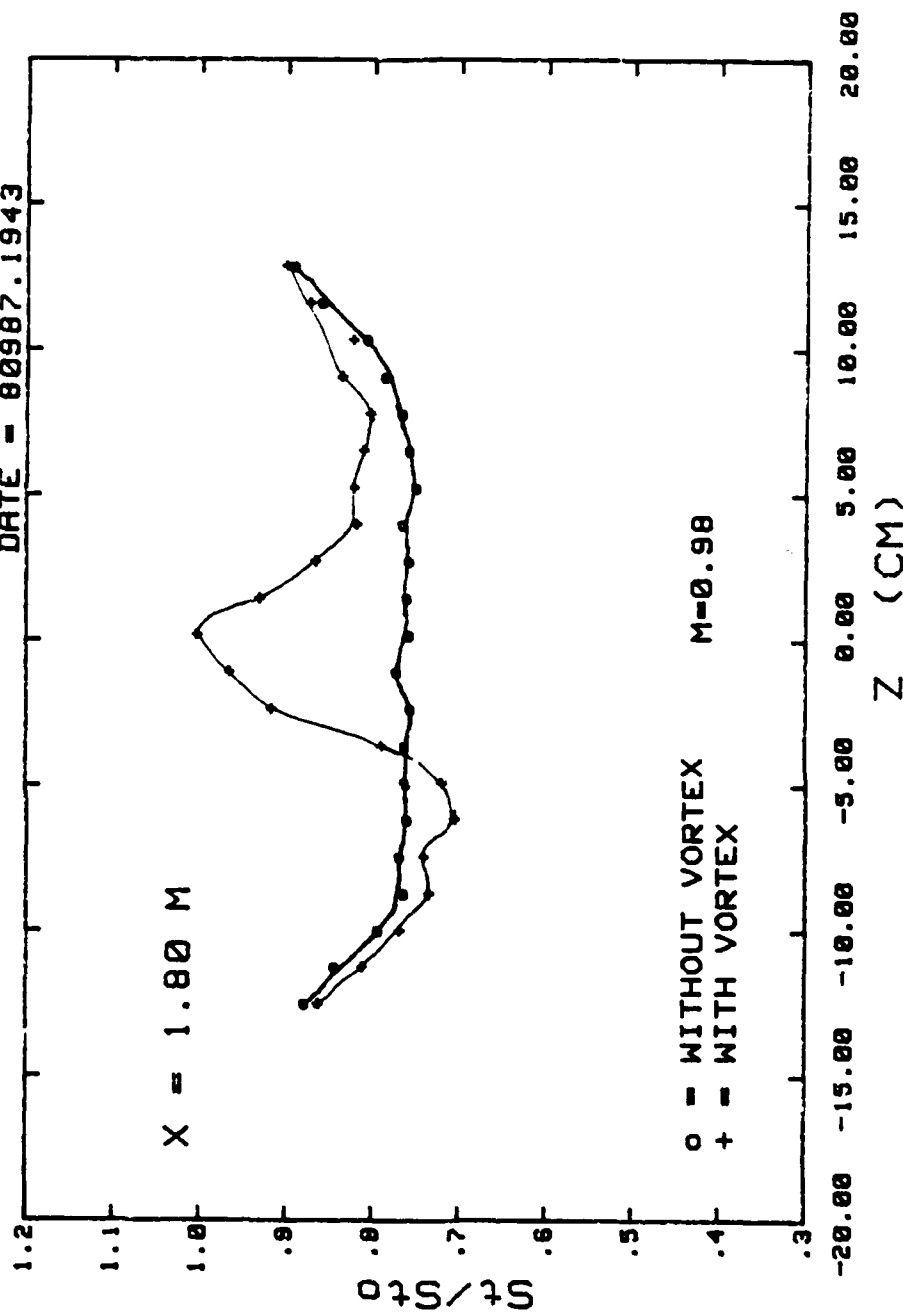


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 4.79 cm

Fig. 33d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

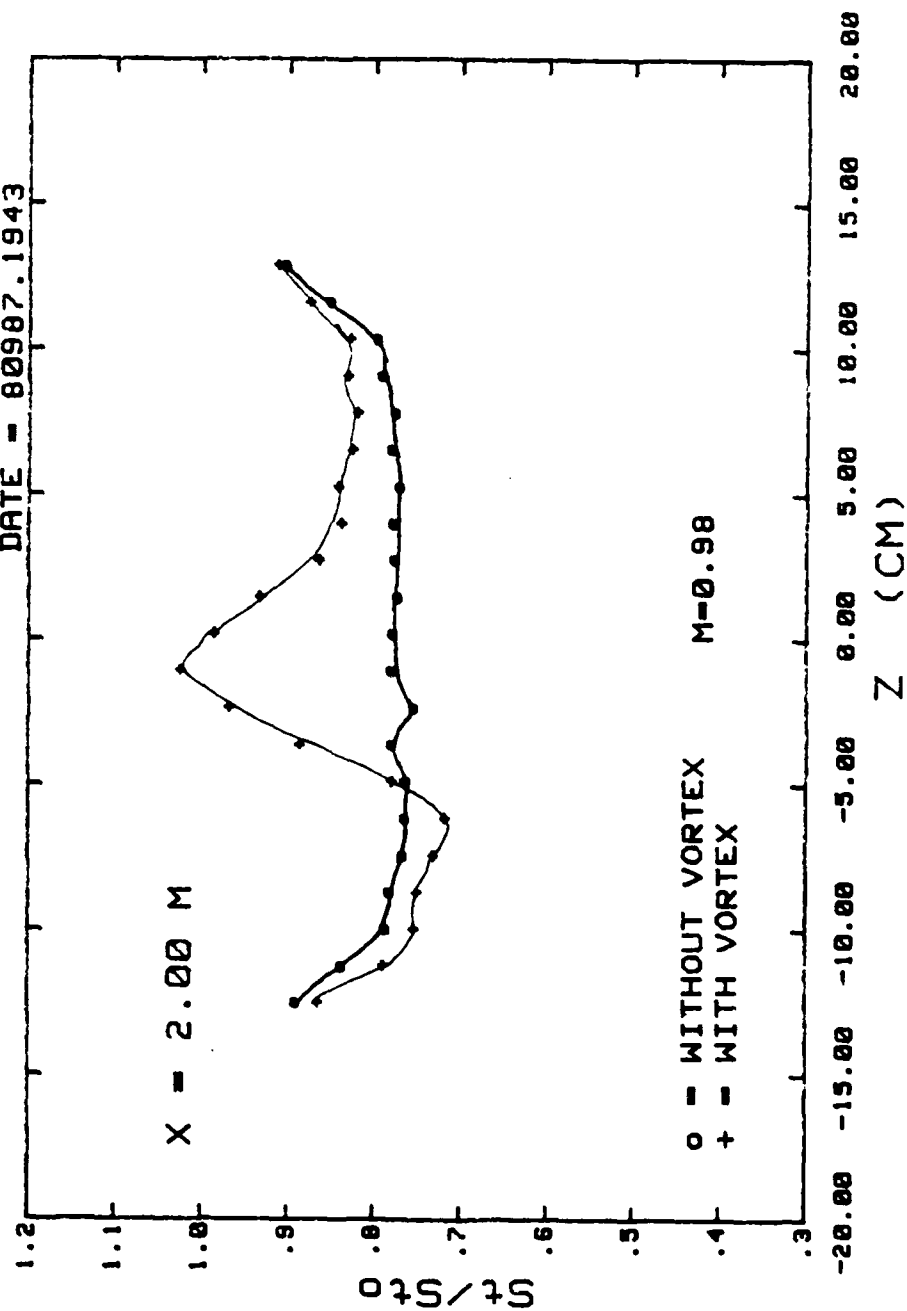
DATE - 80987.1943



FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 4.79 cm  
 Fig. 33e. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80987.1943

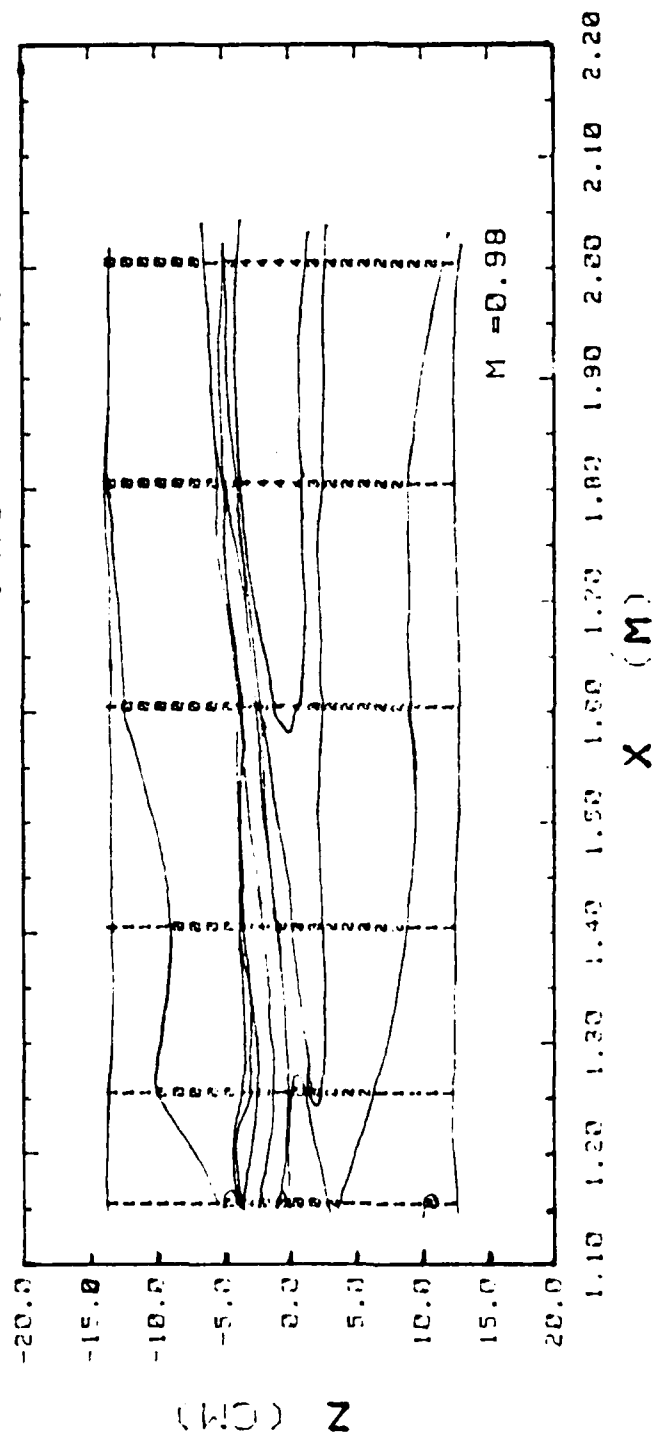


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 4.79 cm

Fig. 33f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 8C987.1943



St/St <sub>f</sub> RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 4.79 cm

Fig. 34. Surface Contours.

# TEMPERATURE PROFILES

DATE- 81187.1502

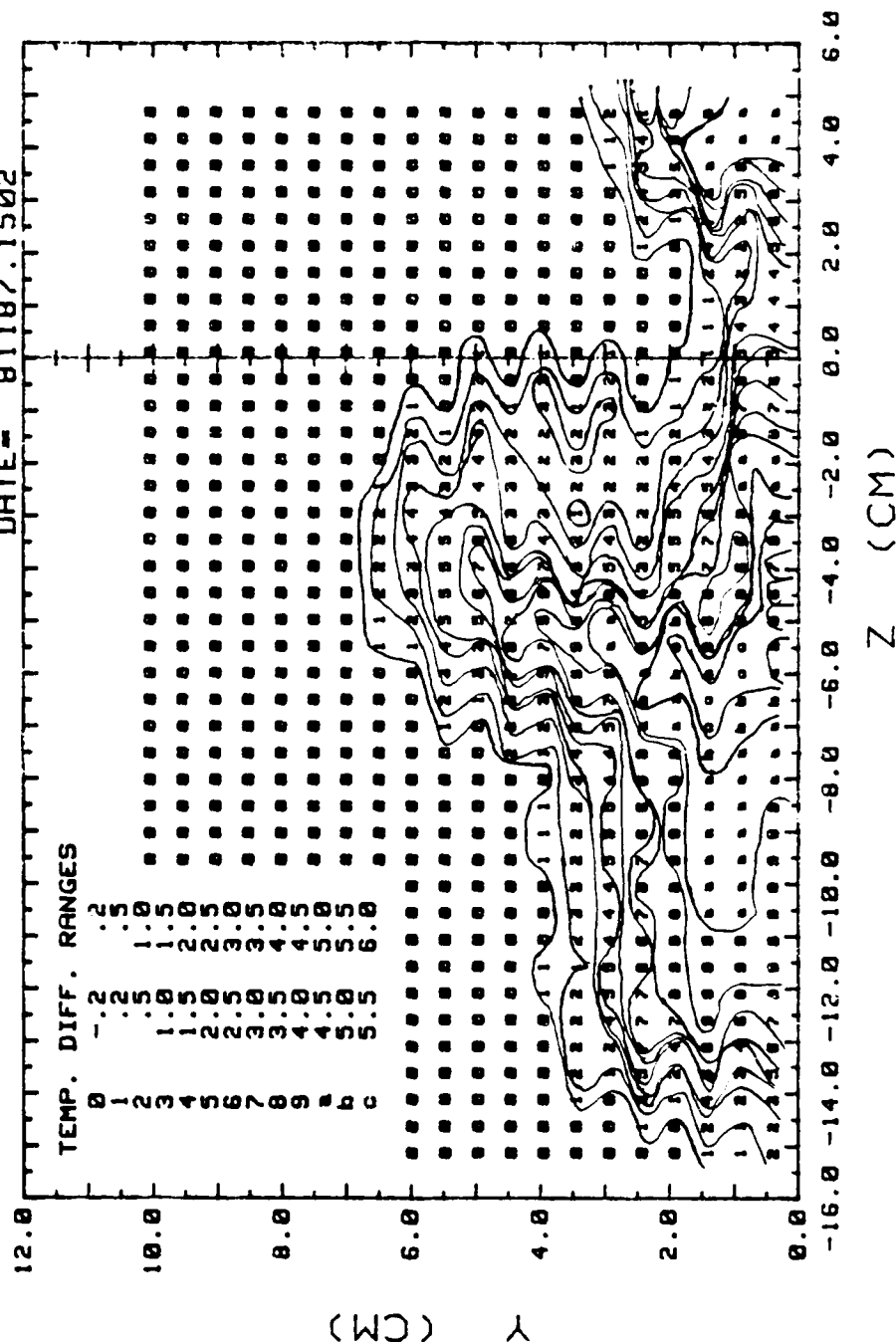


Fig. 35a. EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=1.480$  M, UNHEATED PLATE, VORTEX GEN. AT 4.79 cm



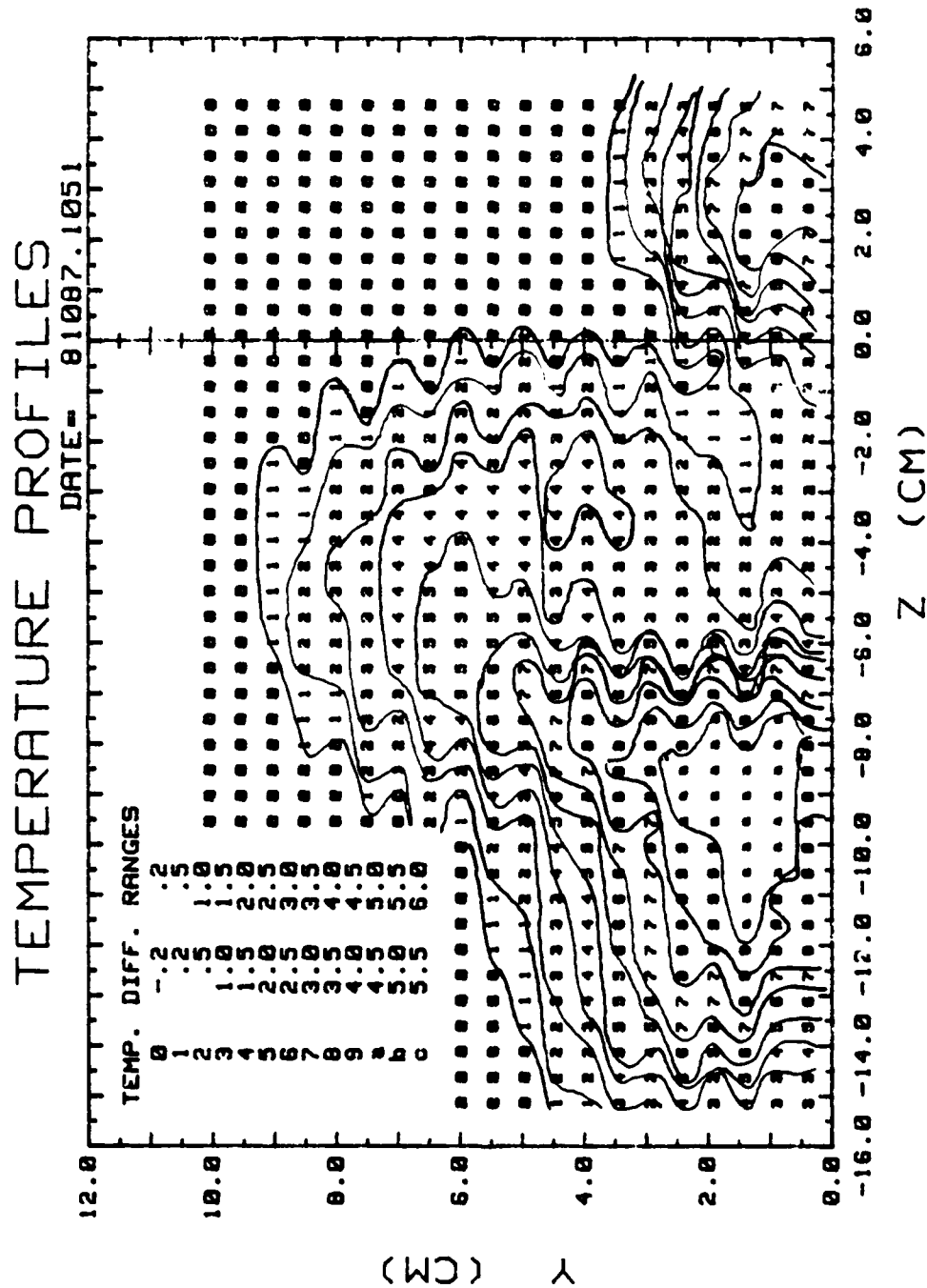


Fig. 35b. EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=1.867$  M, UNHEATED PLATE, VORTEX GEN. AT 4.79 cm

# TEMPERATURE PROFILES

DATE- 81087.1410

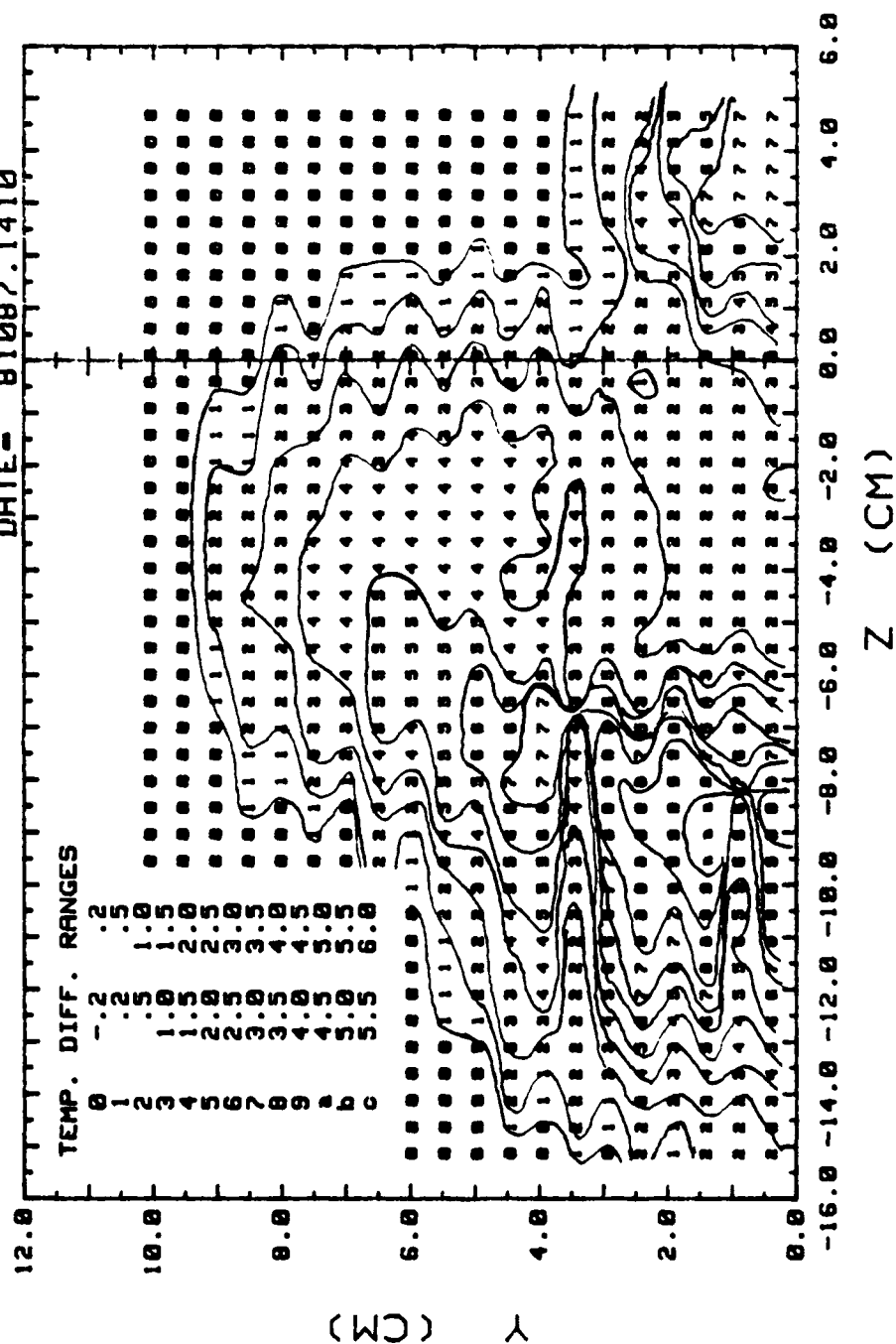


Fig. 35c. EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=2.172$  M, UNHEATED PLATE, VORTEX GEN. AT 4.79 cm

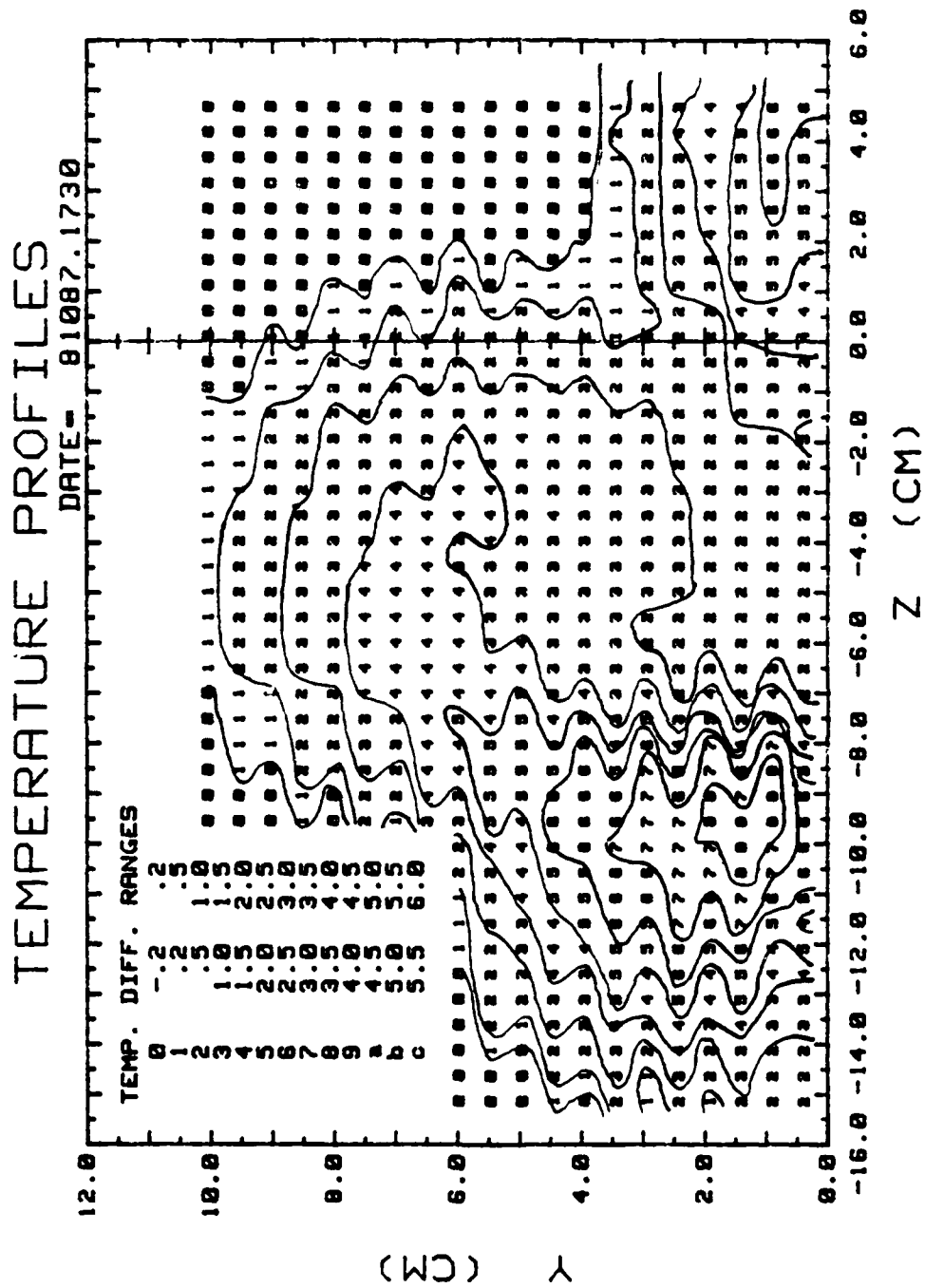


Fig. 35d. EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=2.480$  M, UNHEATED PLATE, VORTEX GEN. AT 4.79 cm

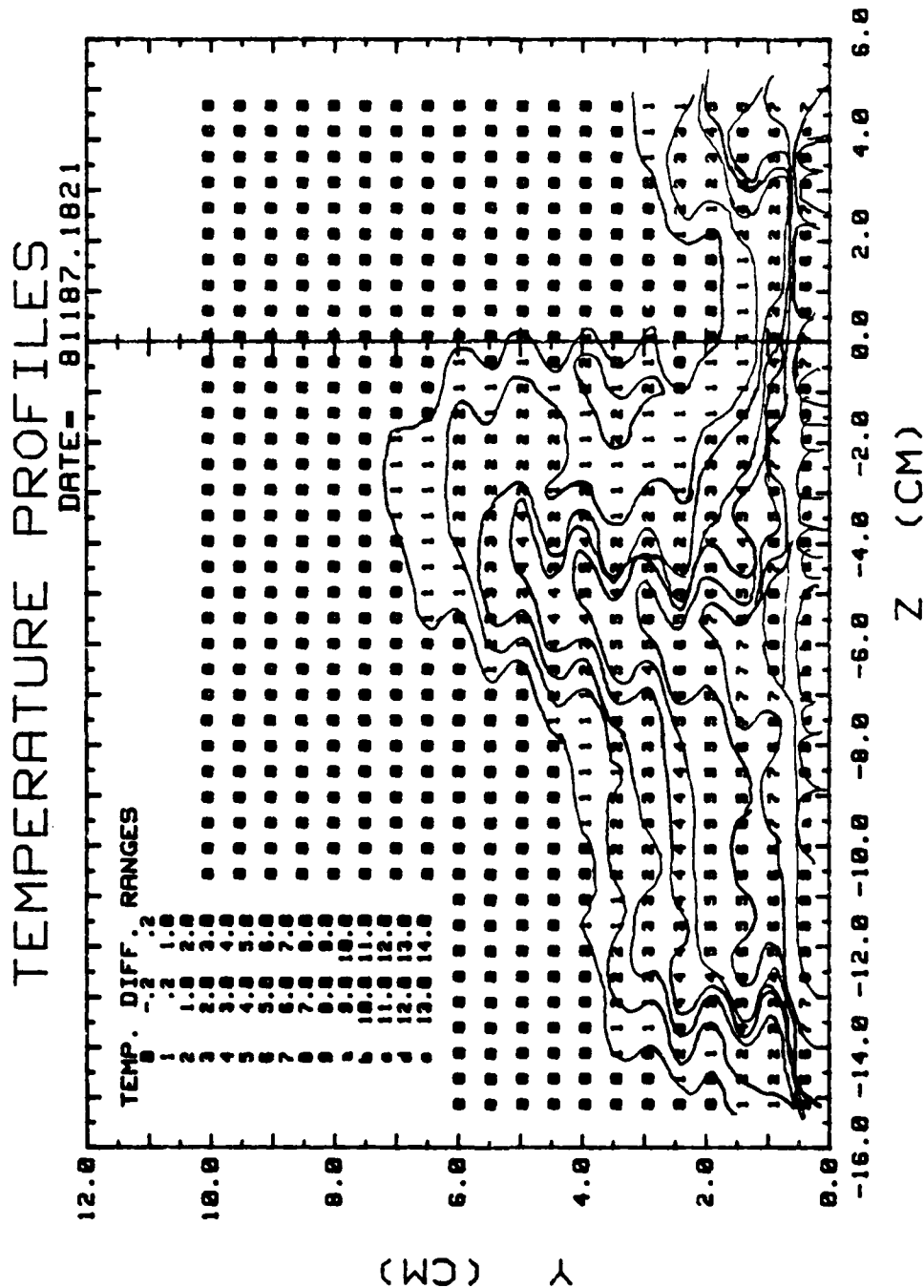


Fig. 36a. EMBEDDED VORTEX, 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=1.480$  M, HEATED PLATE, VORTEX GEN AT 4.79 cm

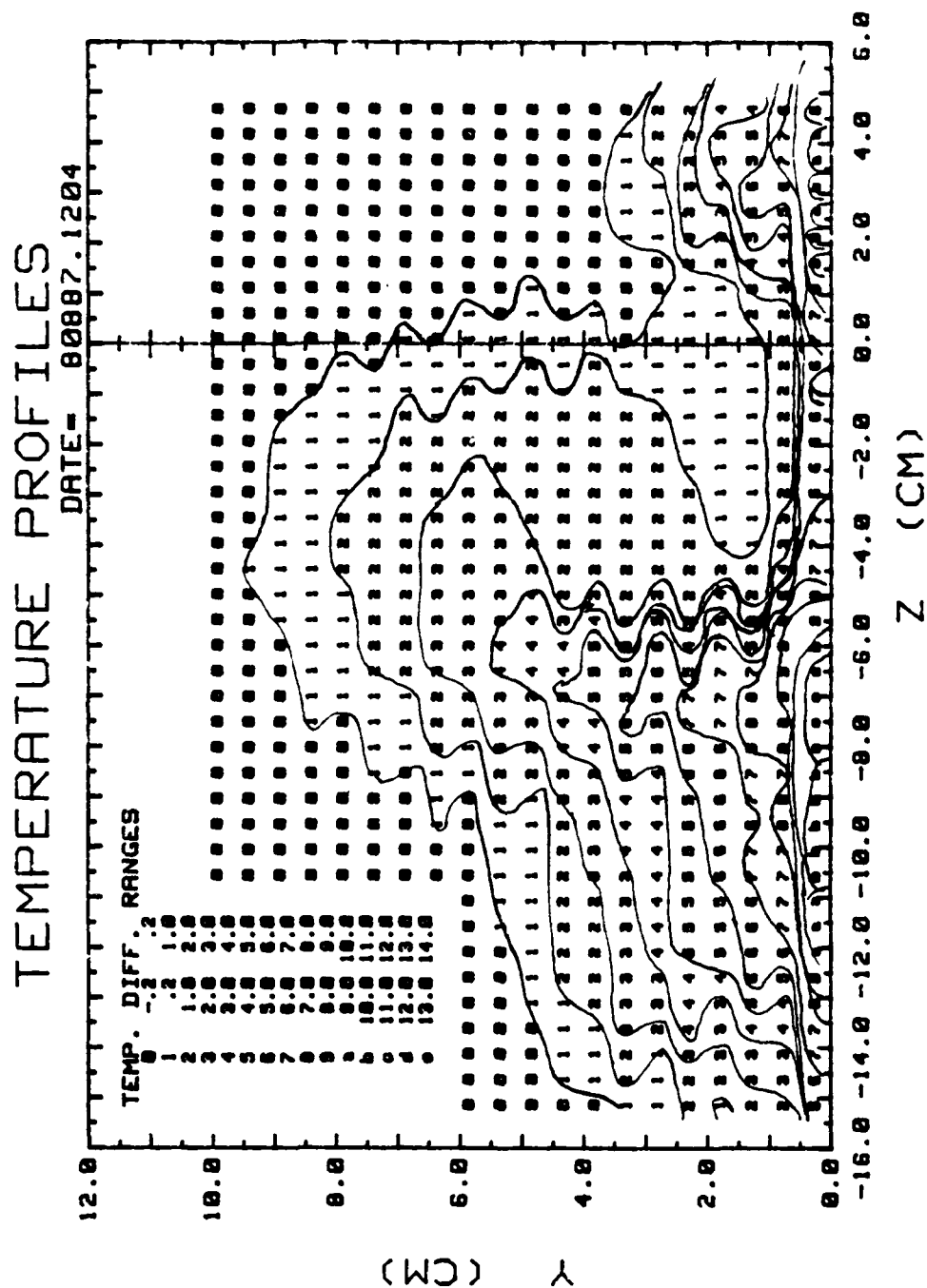


Fig. 36b. EMBEDDED VORTEX, 10 M/S WITH FILM COOLING, M=0.98  
X=1.867 M, HEATED PLATE, VORTEX GEN AT 4.79 cm

# TEMPERATURE PROFILES

DATE= 80887.1902

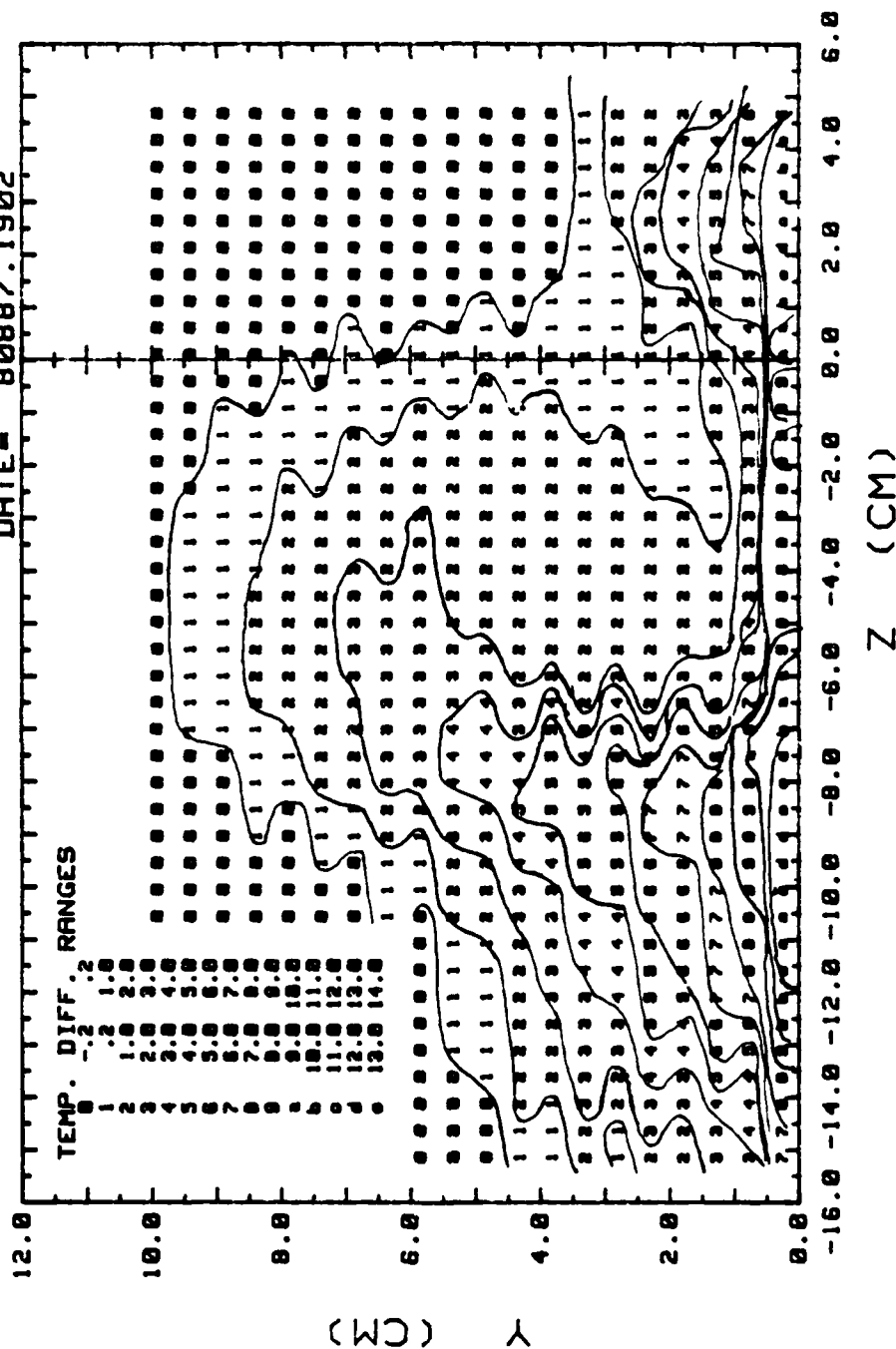


Fig. 36c. EMBEDDED VORTEX, 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=2.172$  M, HEATED PLATE, VORTEX GEN AT 4.79 cm

# STANTON NUMBER RATIOS

DATE - 00407.1529

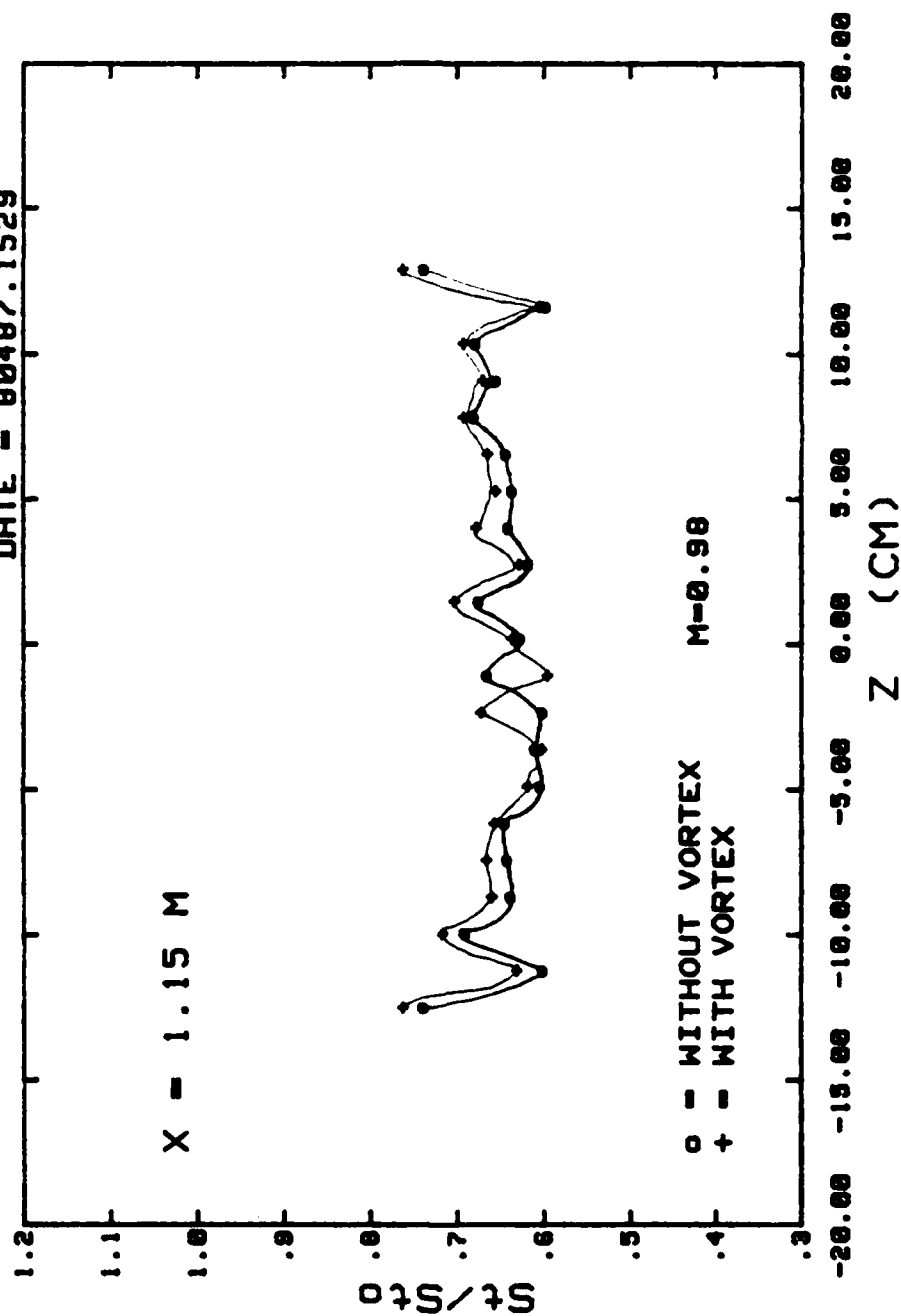
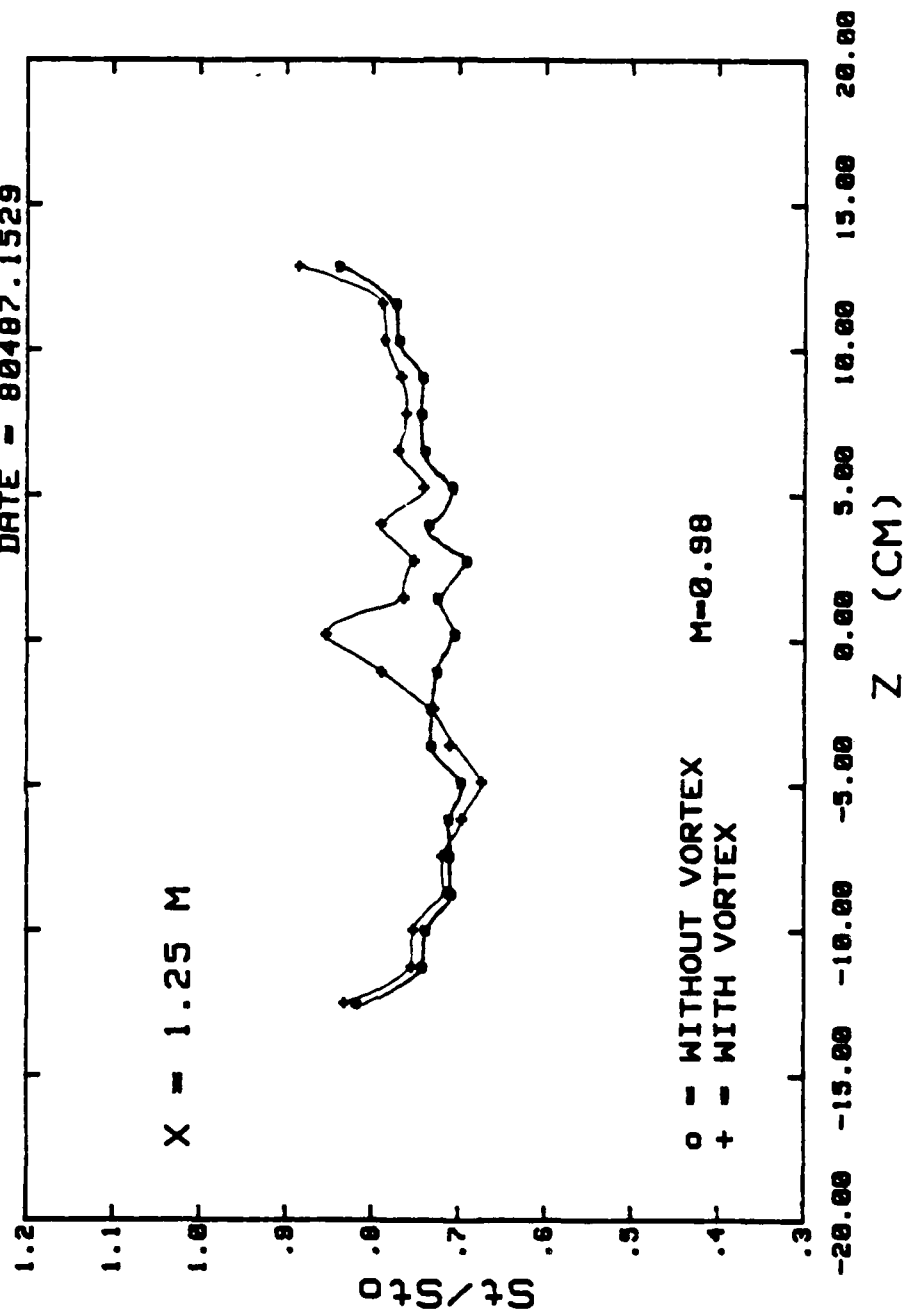


Fig. 37a. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80487.1529



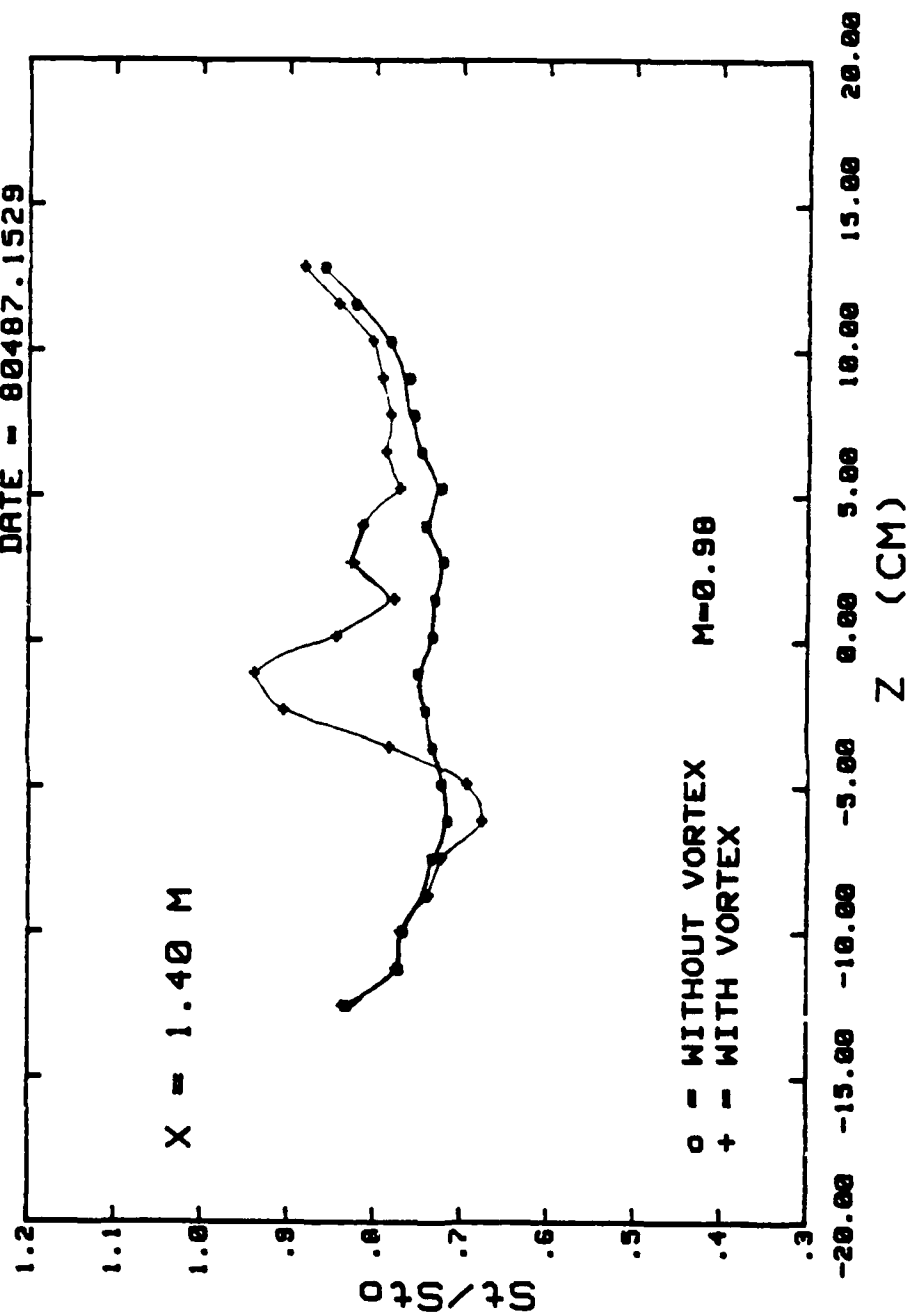
FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 3.52 CM

Fig. 37b. Spanwise Variations of Stanton Number Ratios.



# STANTON NUMBER RATIOS

DATE - 80487.1529

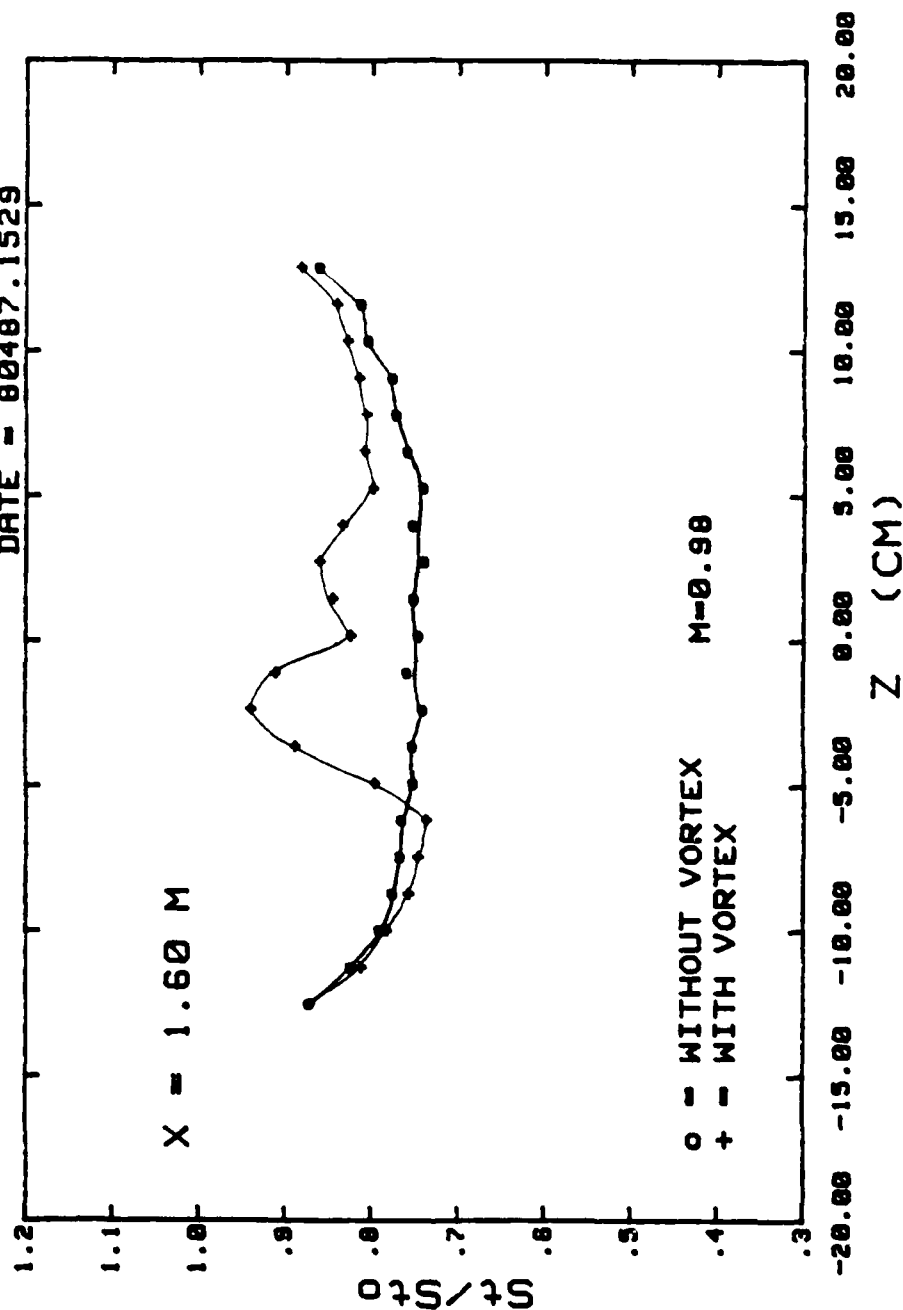


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 3.52 cm

Fig. 37c. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80487.1529

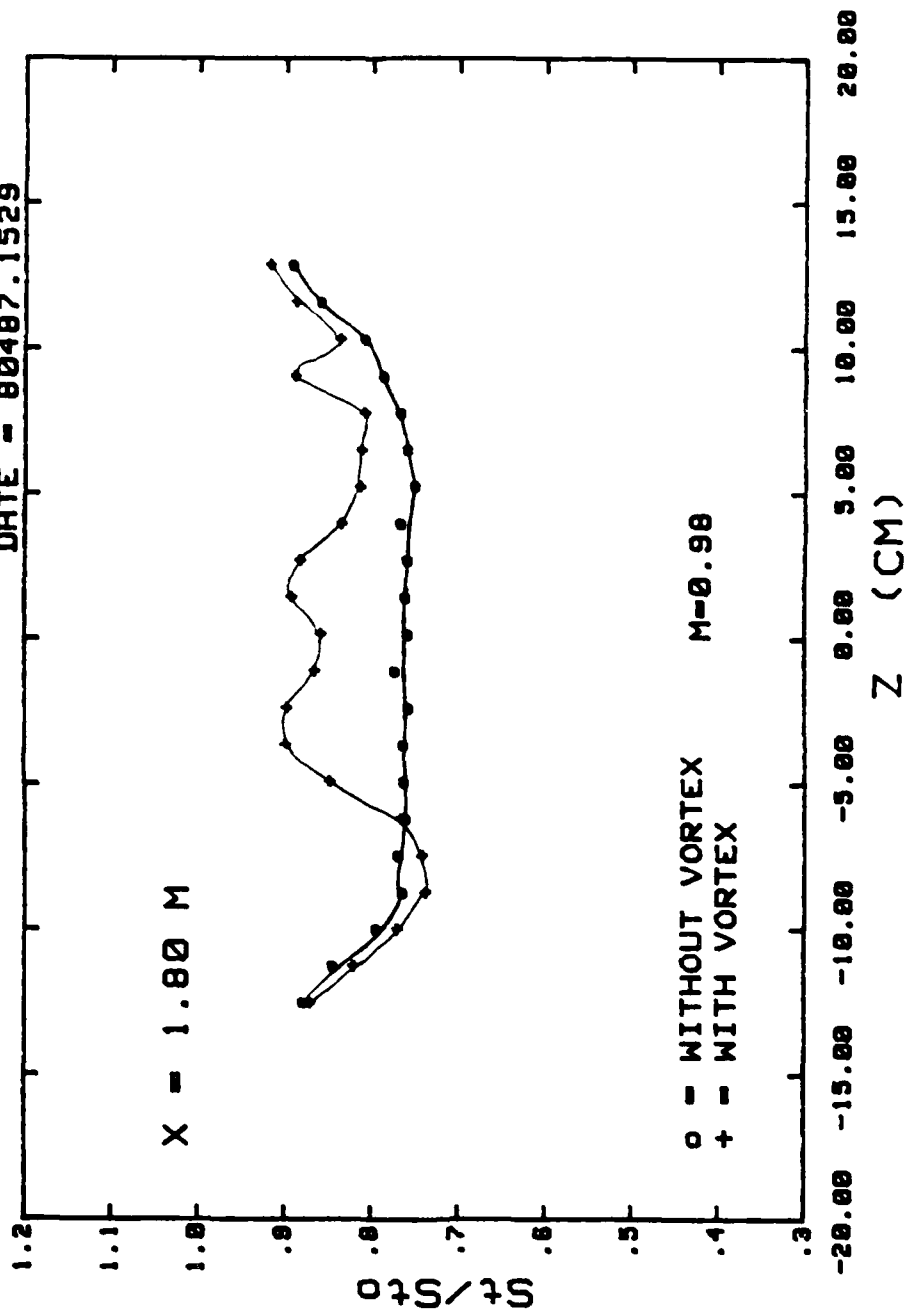


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 3.52 cm

Fig. 37d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 00407.1529

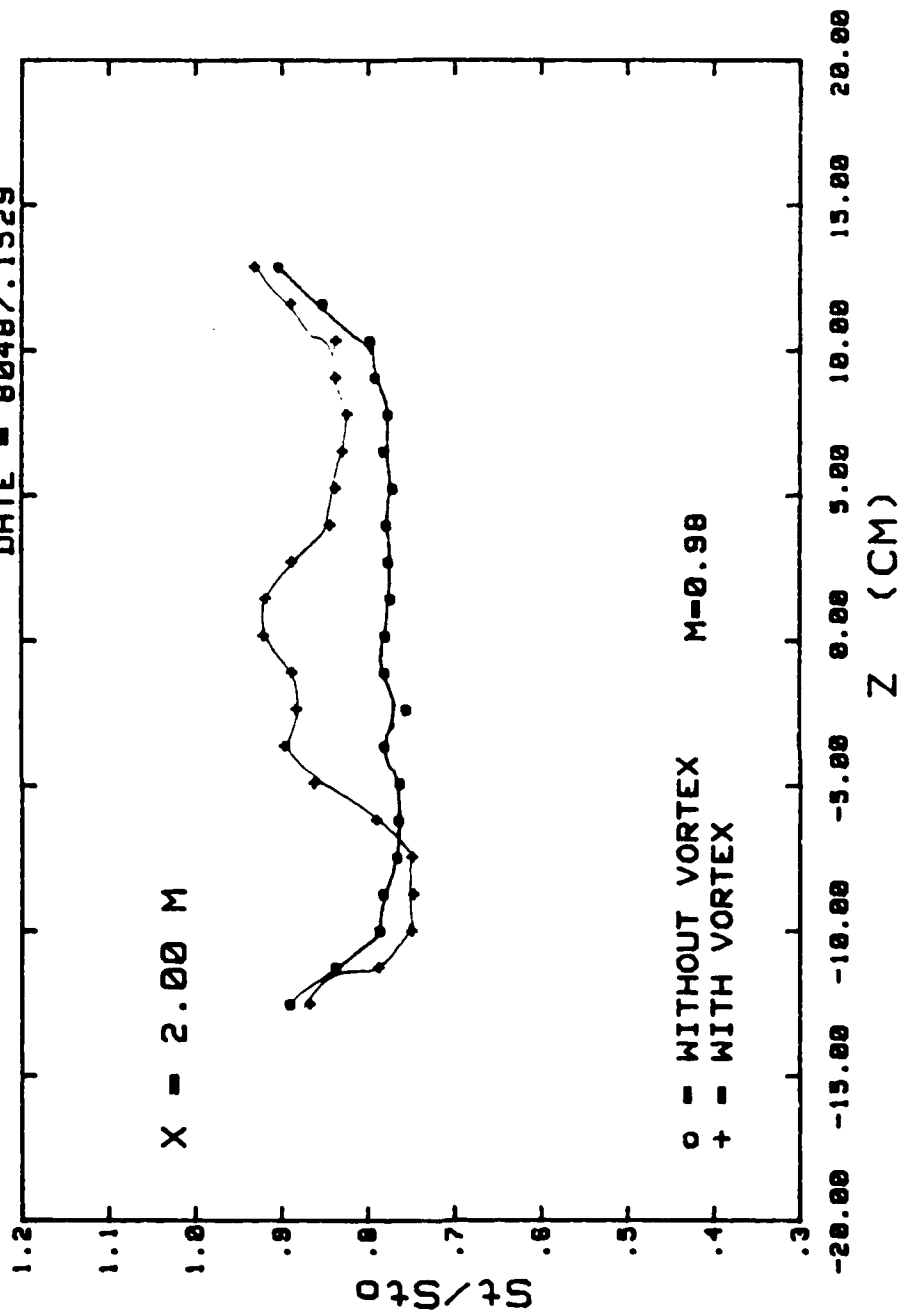


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 3.52 cm

Fig. 37e. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80487.1529

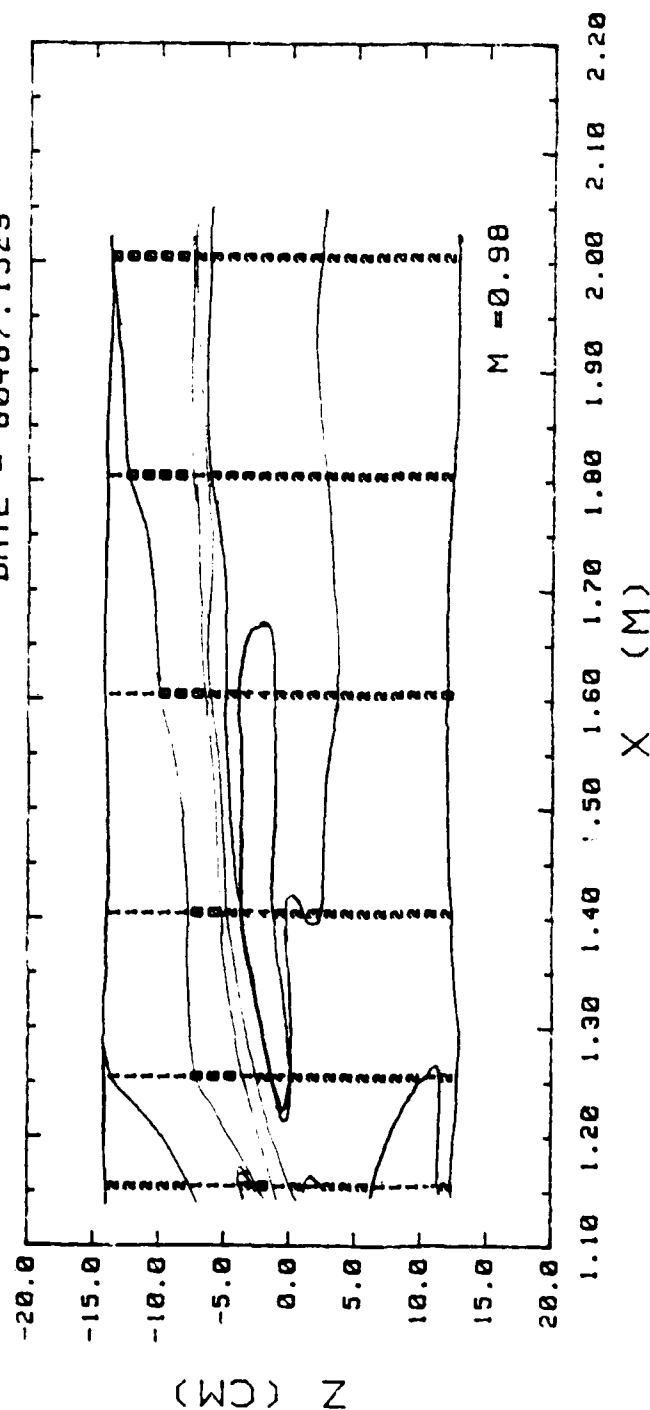


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 3.52 cm

Fig.37f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 80487.1529



St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 3.52 cm

Fig. 38. Surface Contour.

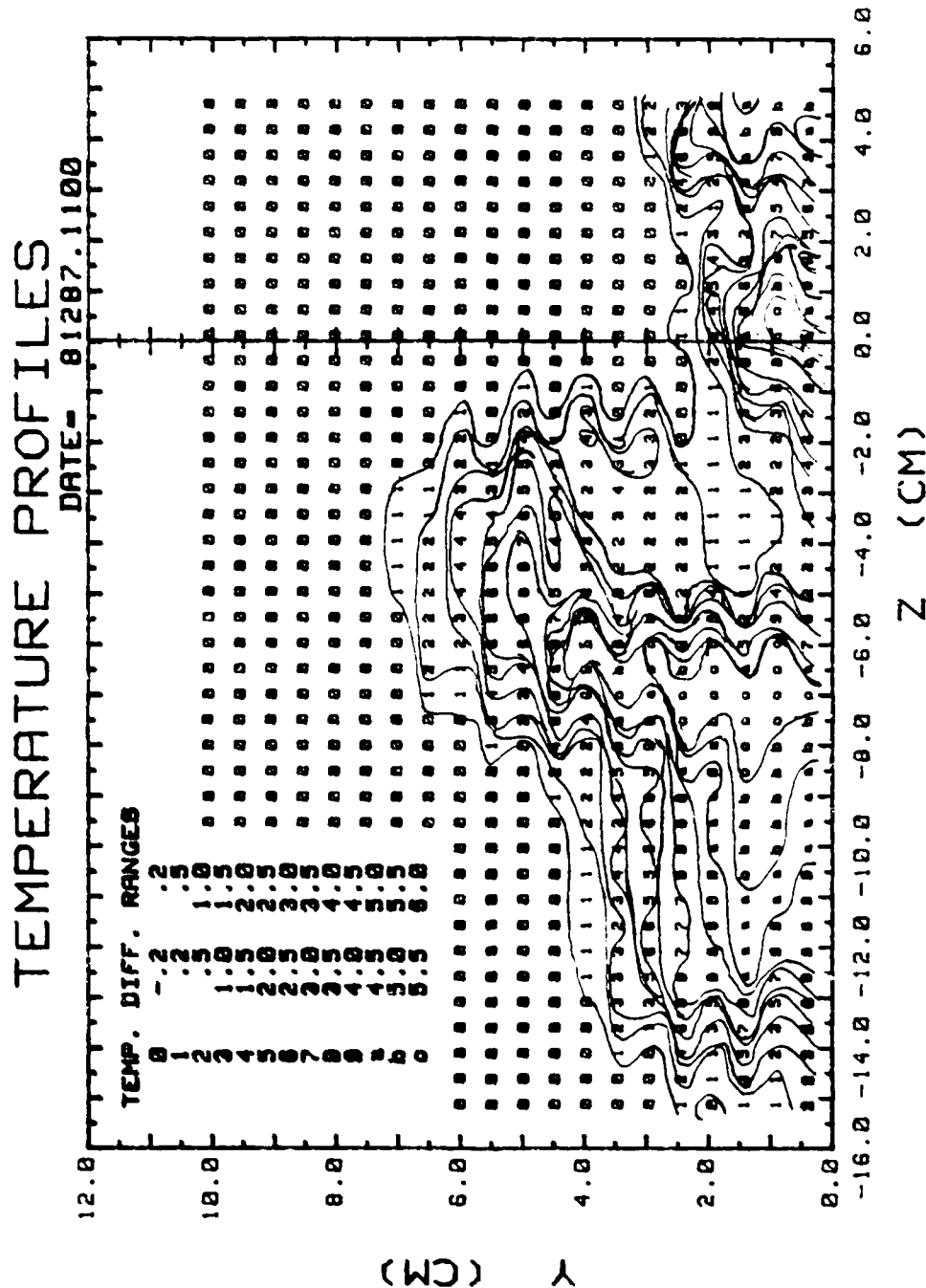


Fig. 39. EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=0.98$   
 $X=1.480$  M, UNHEATED PLATE, VORTEX GEN. AT 3.52 cm

# STANTON NUMBER RATIOS

DATE - 00407.1553

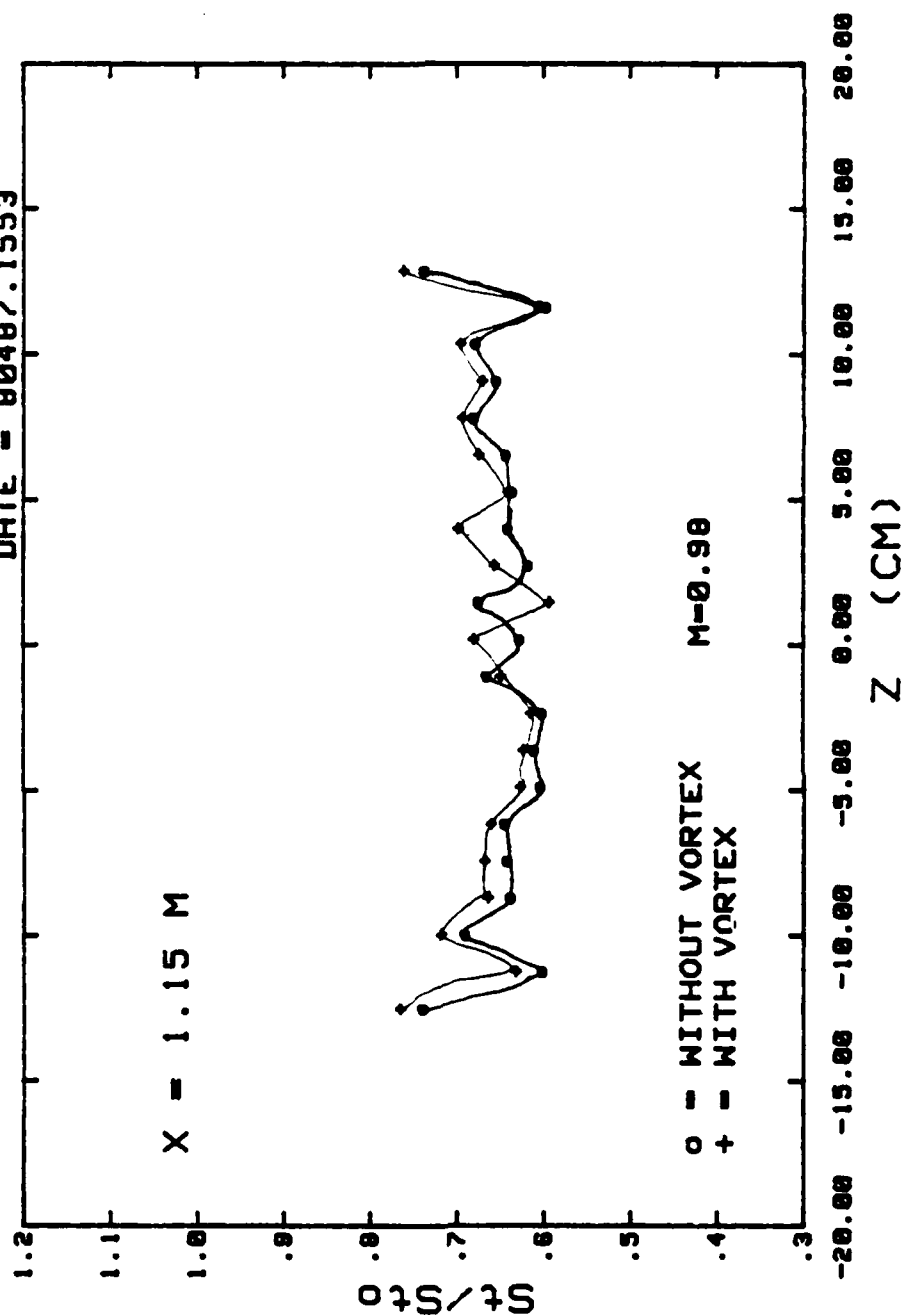
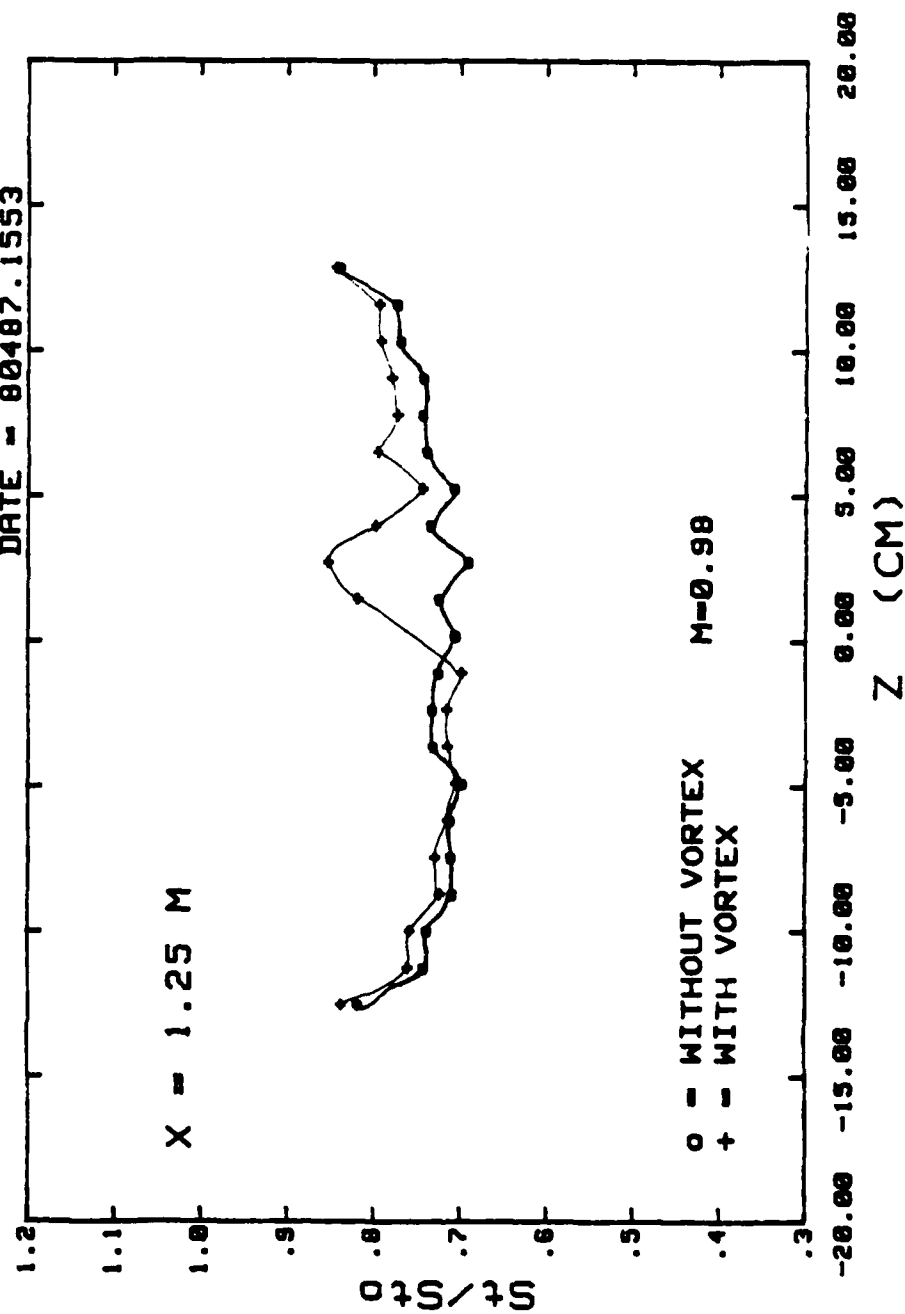


Fig. 40a. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80487.1553



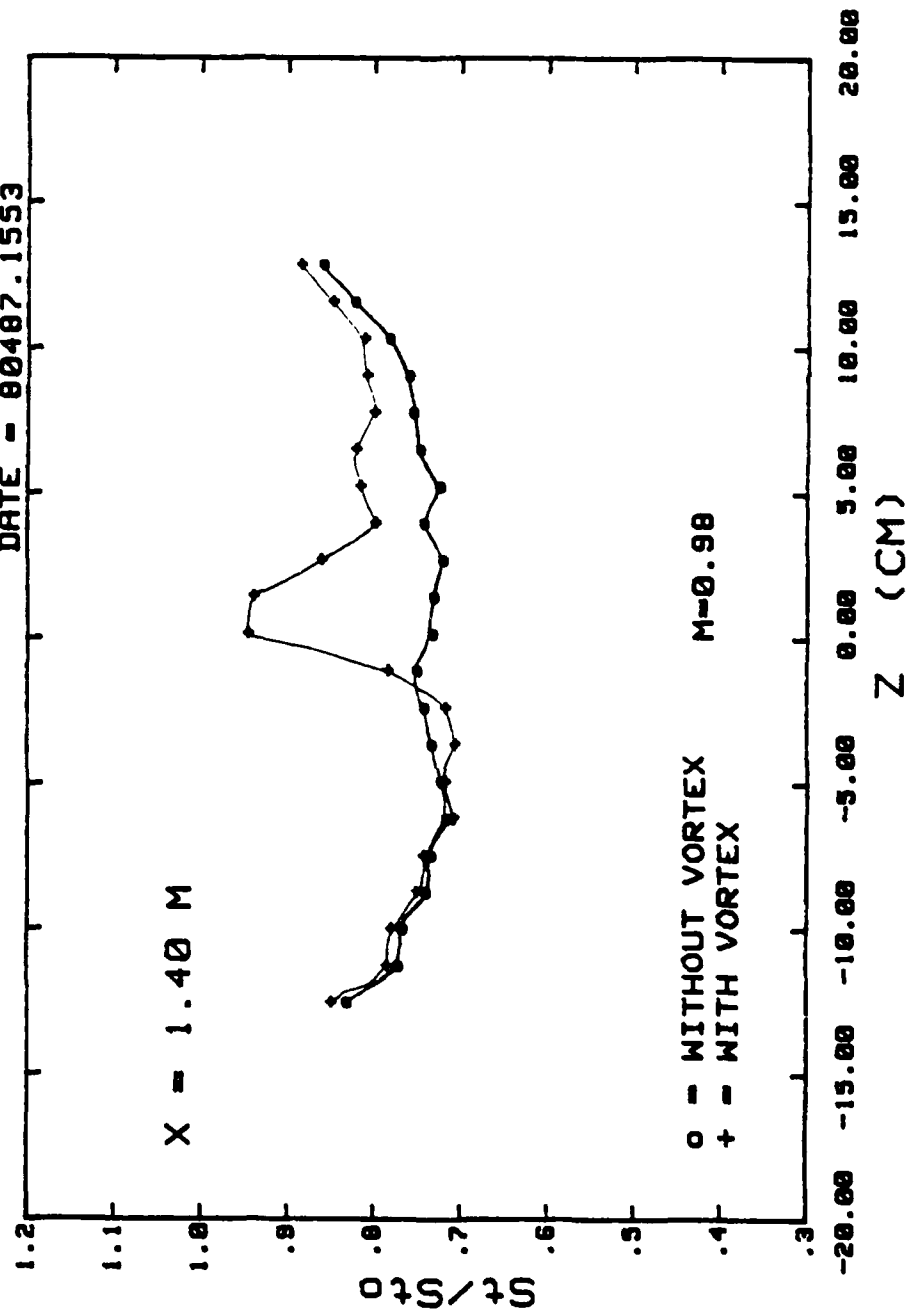
FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 6.06 cm

Fig. 40b. Spanwise Variations of Stanton Number Ratios.



# STANTON NUMBER RATIOS

DATE - 80487.1553

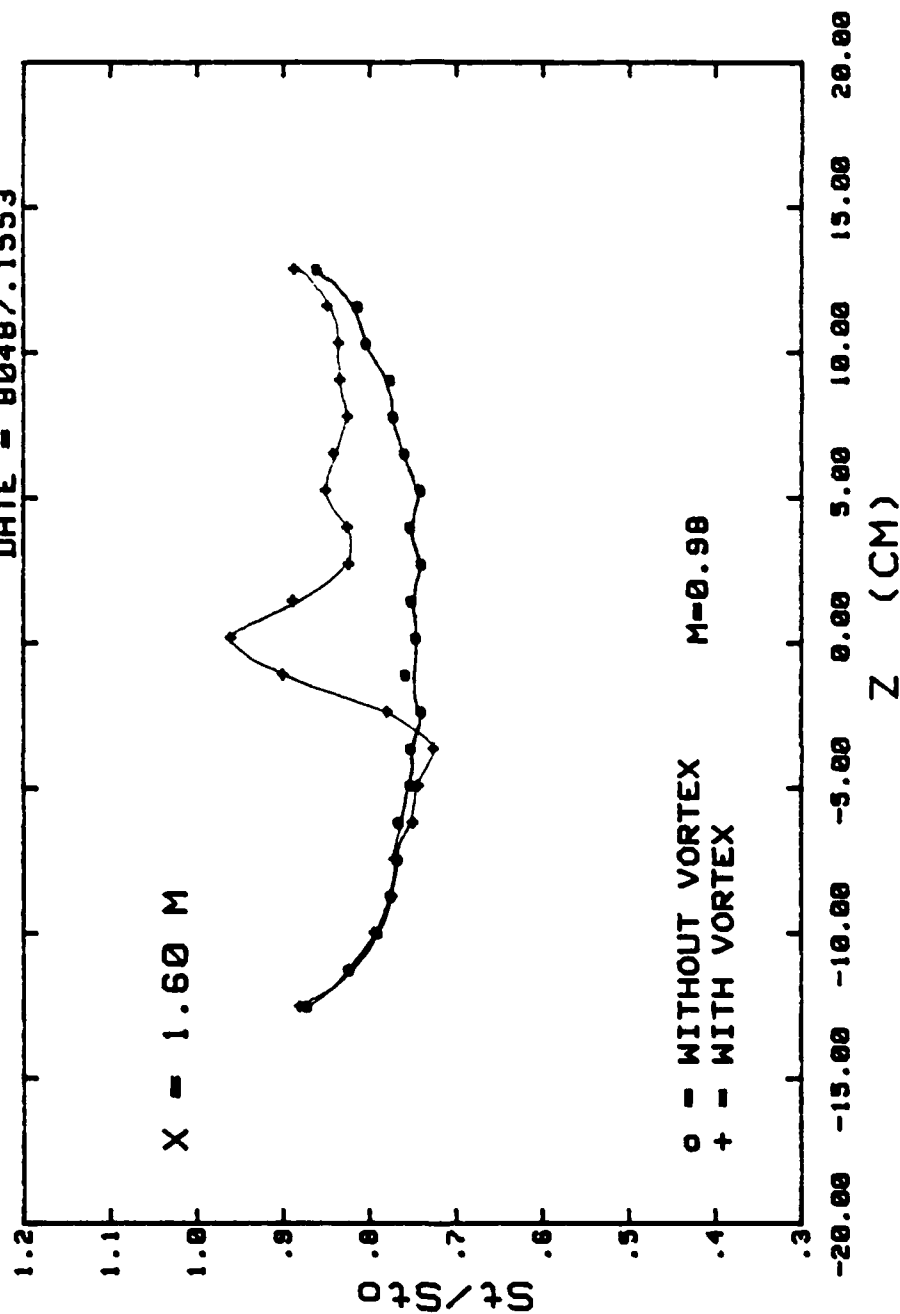


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 6.06 cm

Fig. 40c. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80487.1553

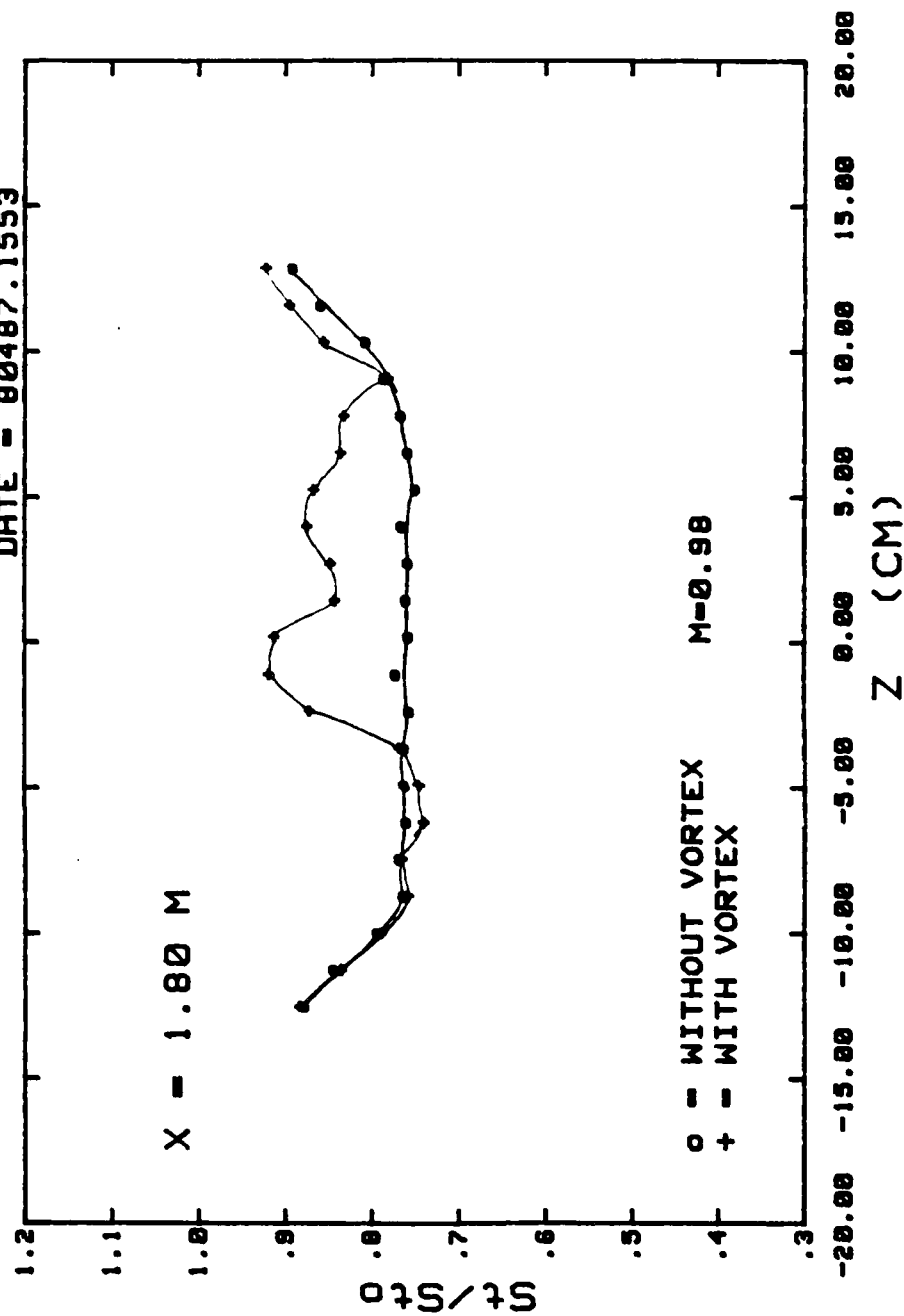


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 6.06 cm

Fig. 40d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 00407.1553

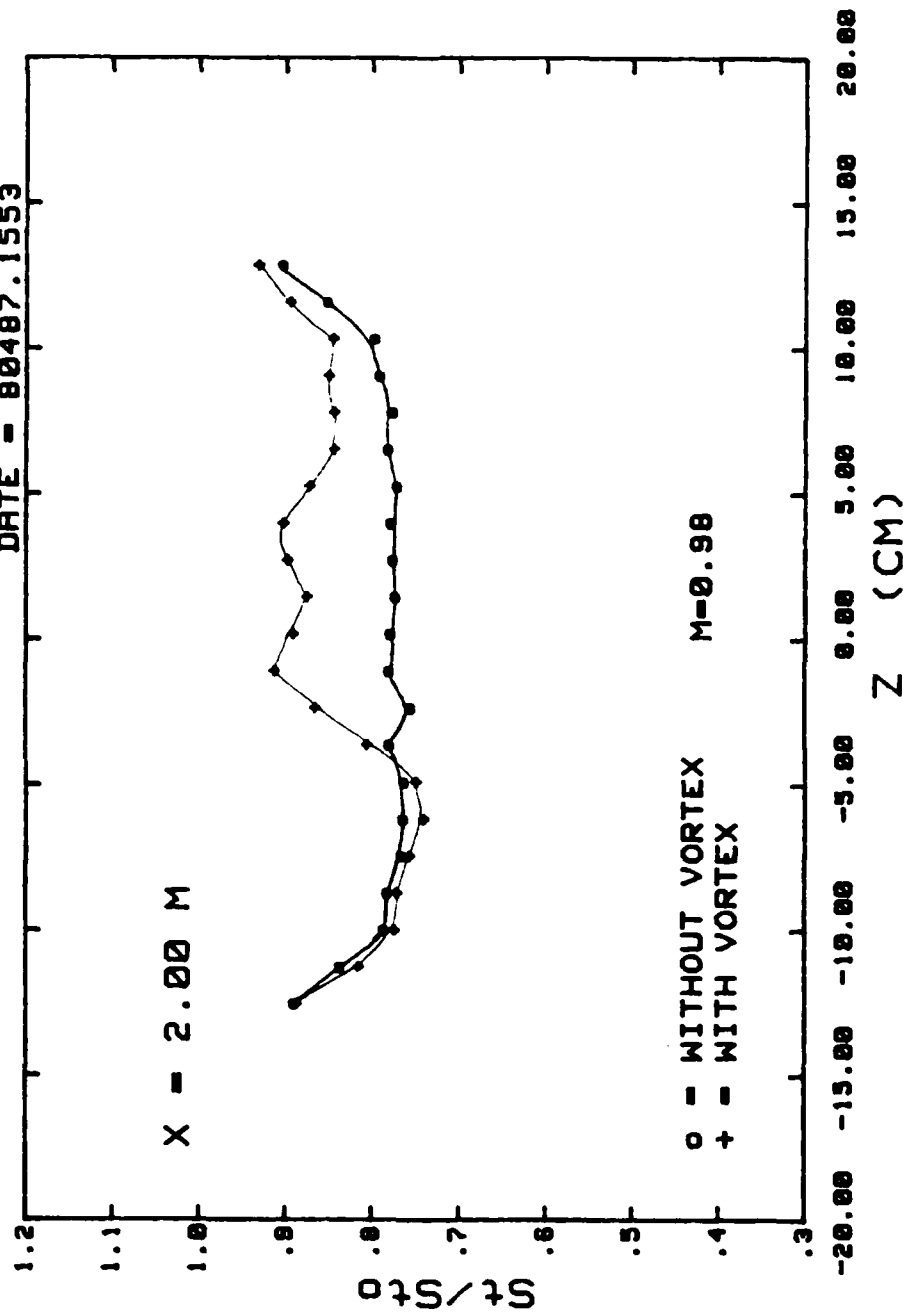


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 6.06 cm

Fig. 40e. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80487.1553

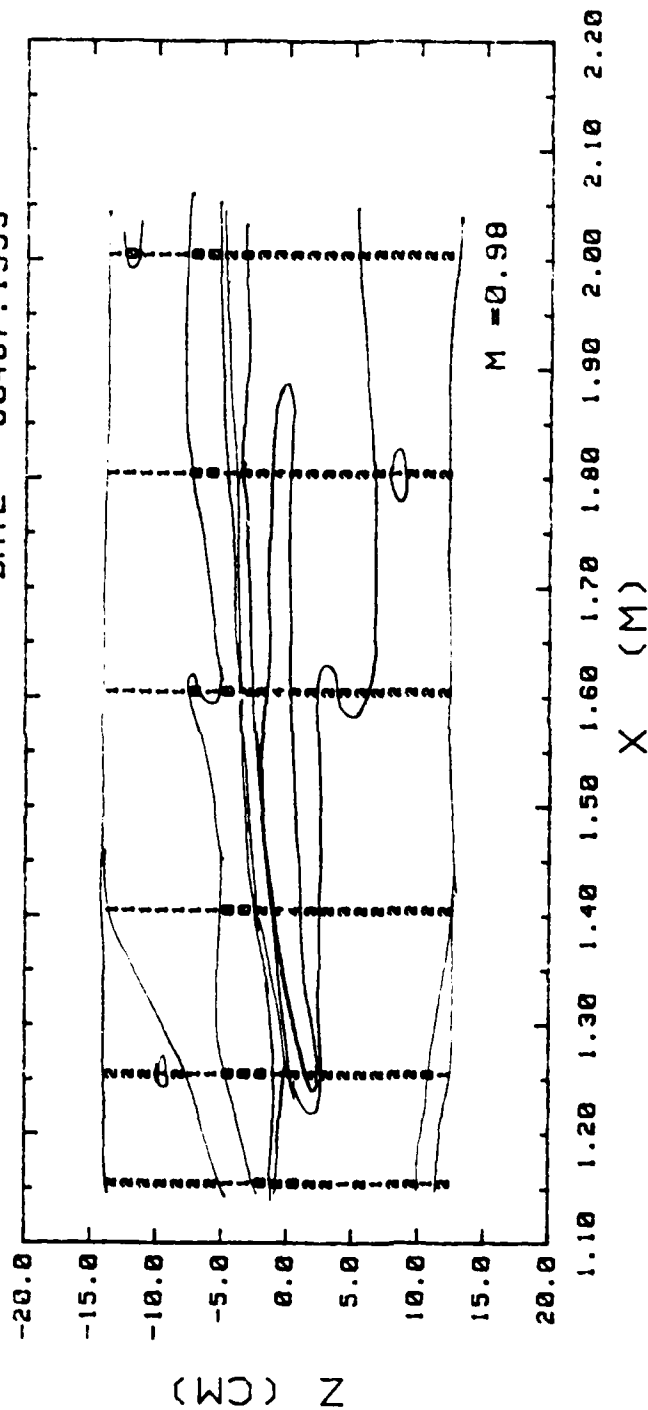


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN.#2 AT 6.06 cm

Fig. 40f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 80487.1553



St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 6.06 cm

Fig. 41. Surface Contour.

# TEMPERATURE PROFILES

DATE- 81287.1407

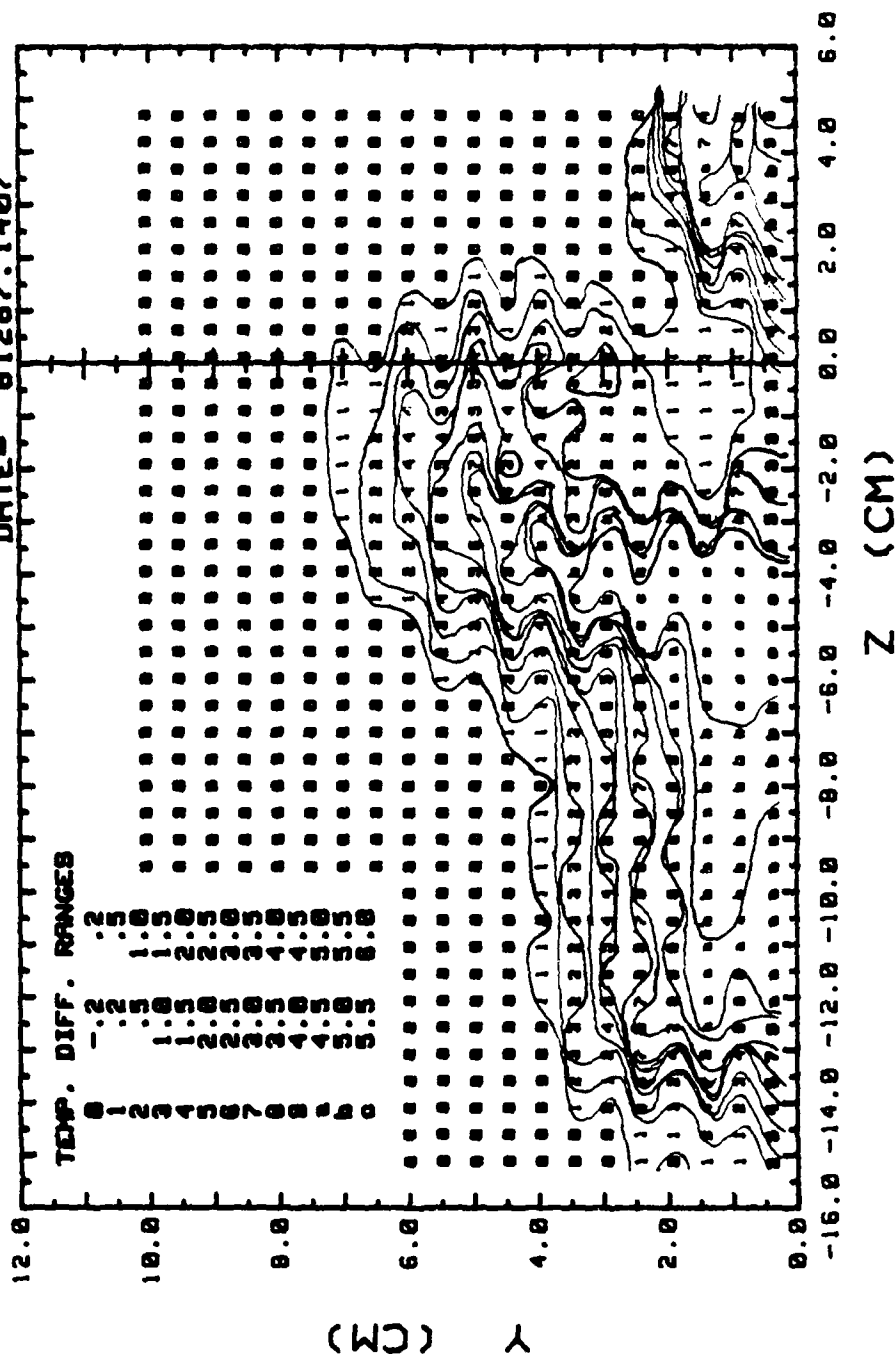
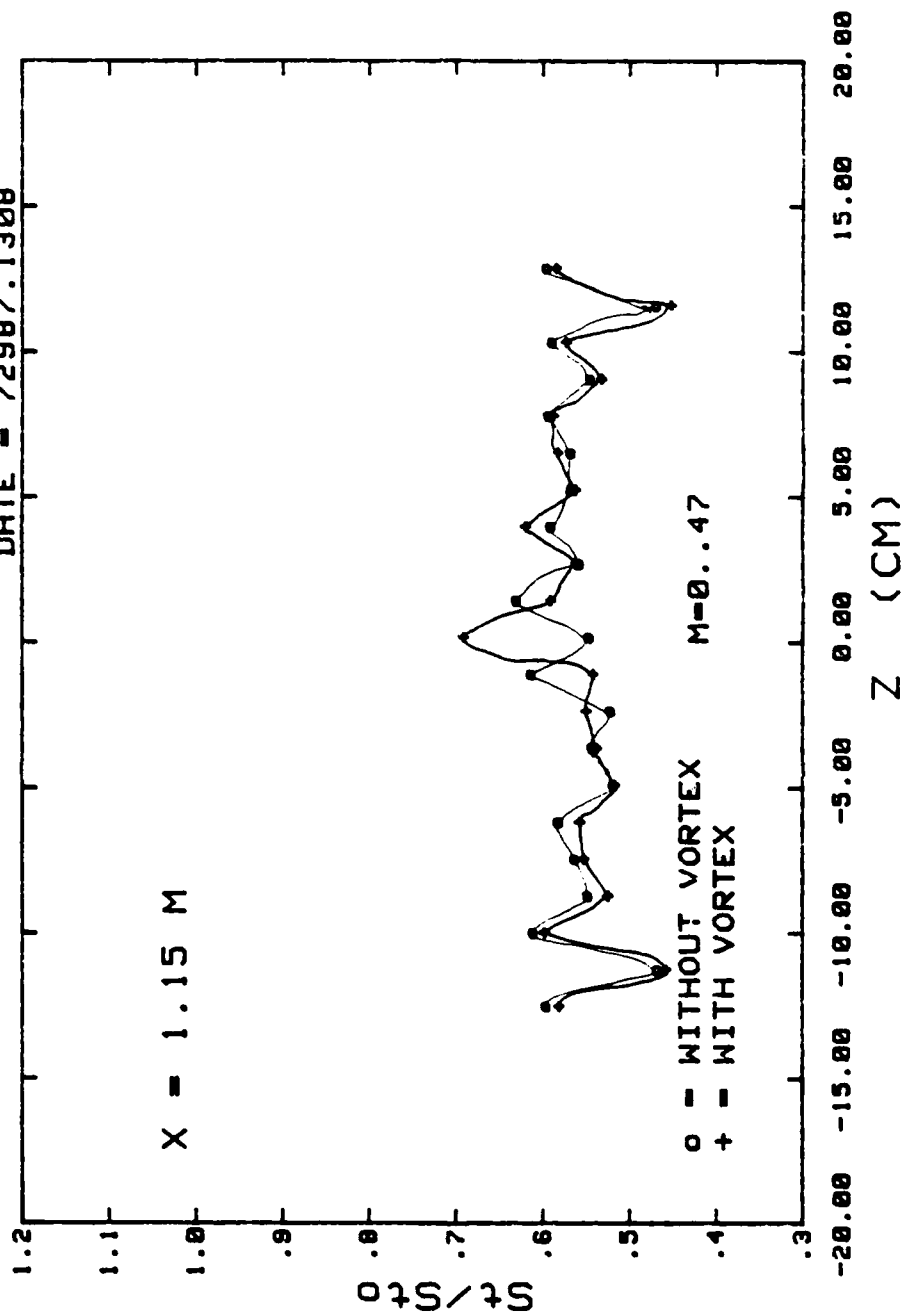


Fig. 42. EMBEDDED VORTEX 10 M/S WITH FILM COOLING  
X=1.480 M, UNHEATED PLATE, VORTEX GEN. AT 6.06 CM

# STANTON NUMBER RATIOS

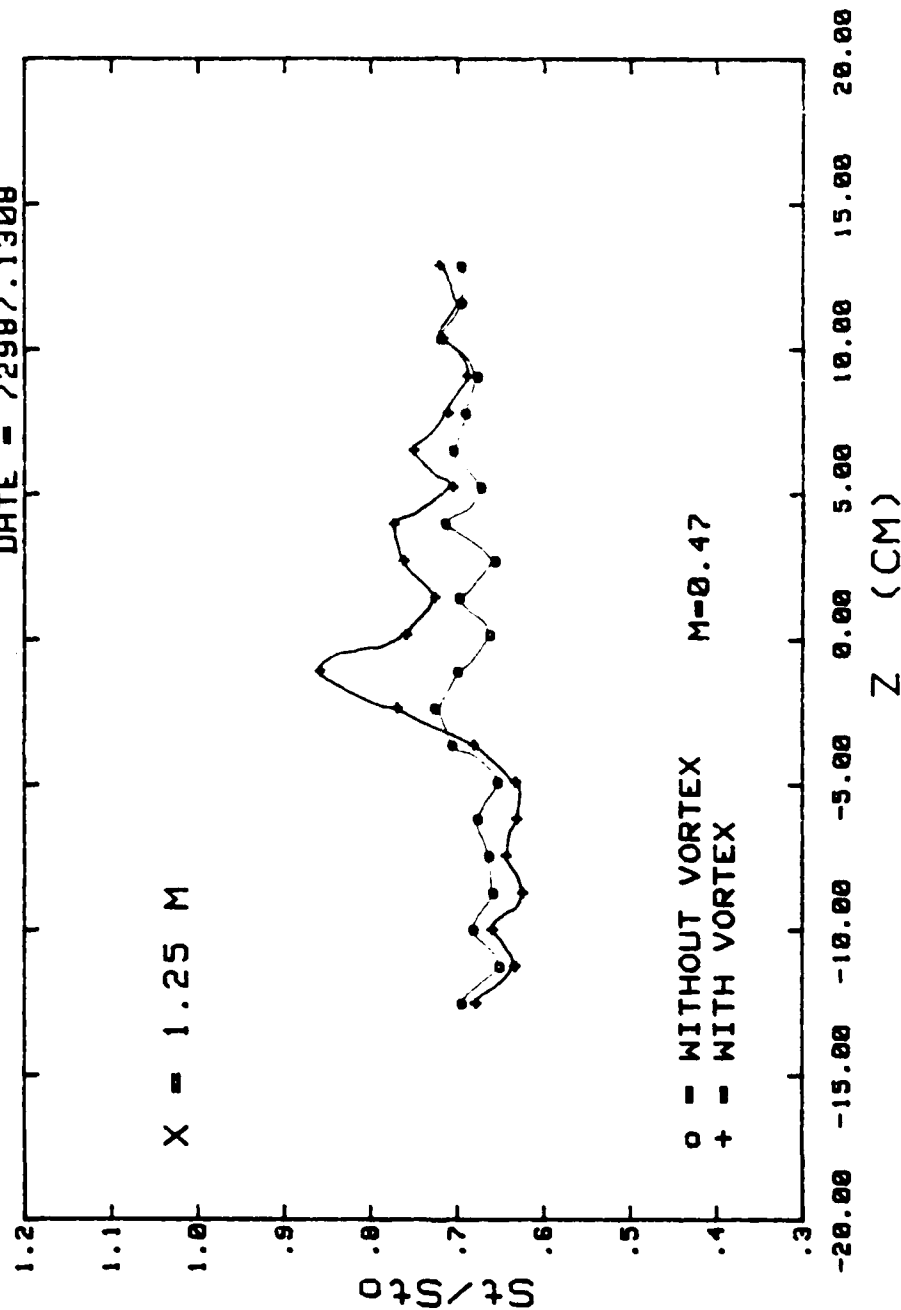
DATE = 72987.1308



FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm  
Fig. 43a. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 72987.1300



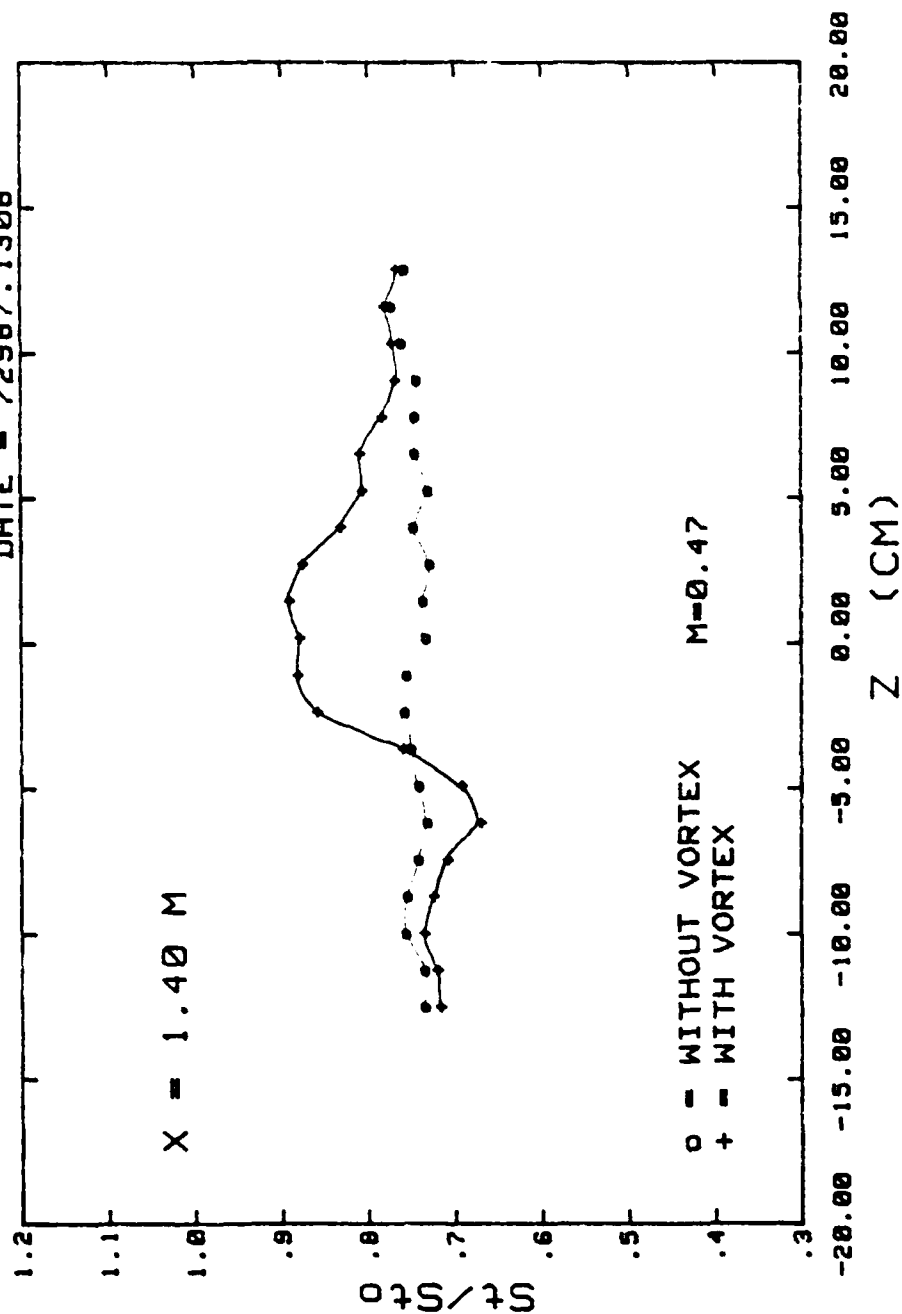
FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 43b. Spanwise Variations of Stanton Number Ratios.



# STANTON NUMBER RATIOS

DATE = 72987.1308

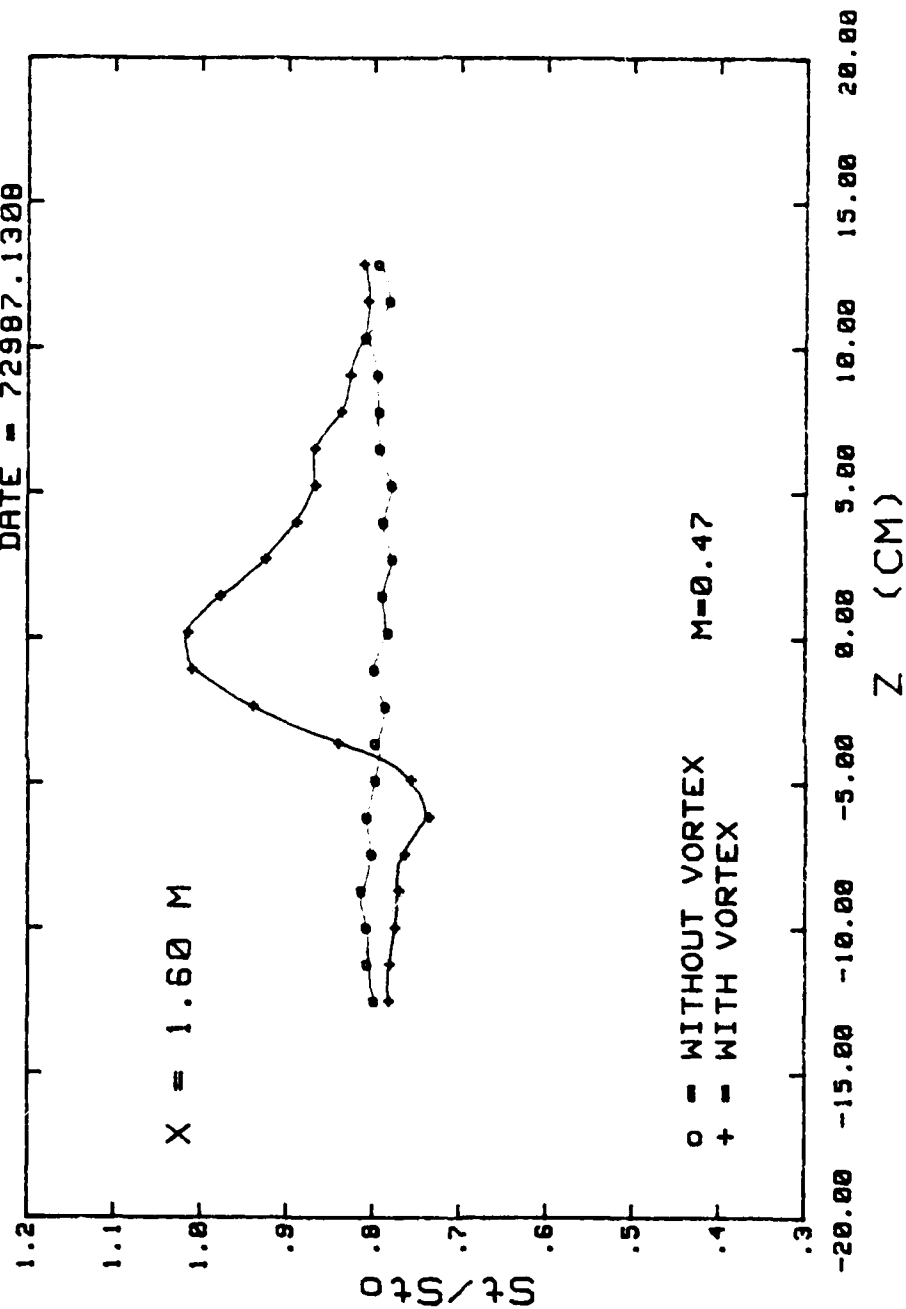


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 43c. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 72987.1308

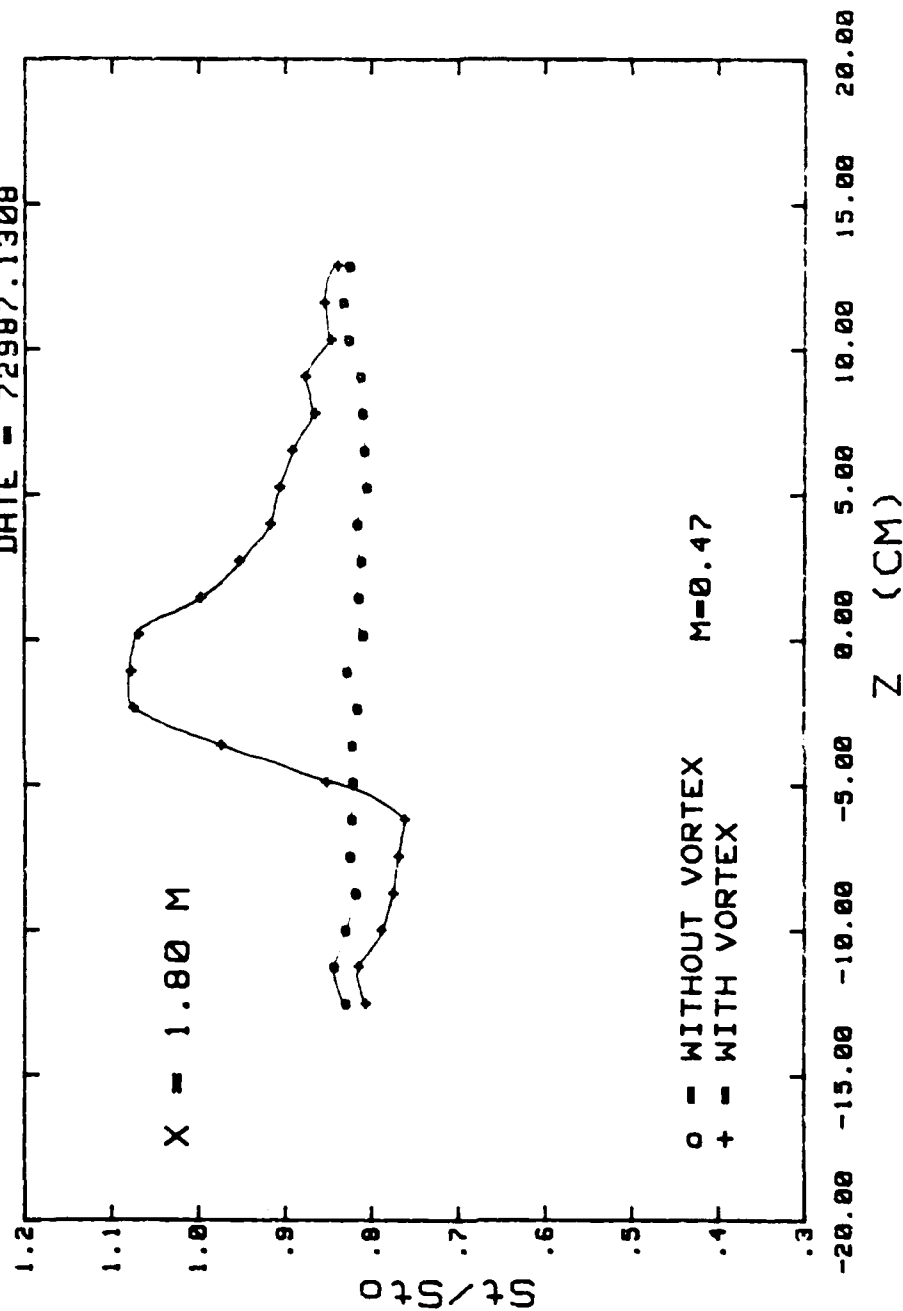


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm

Fig. 43d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

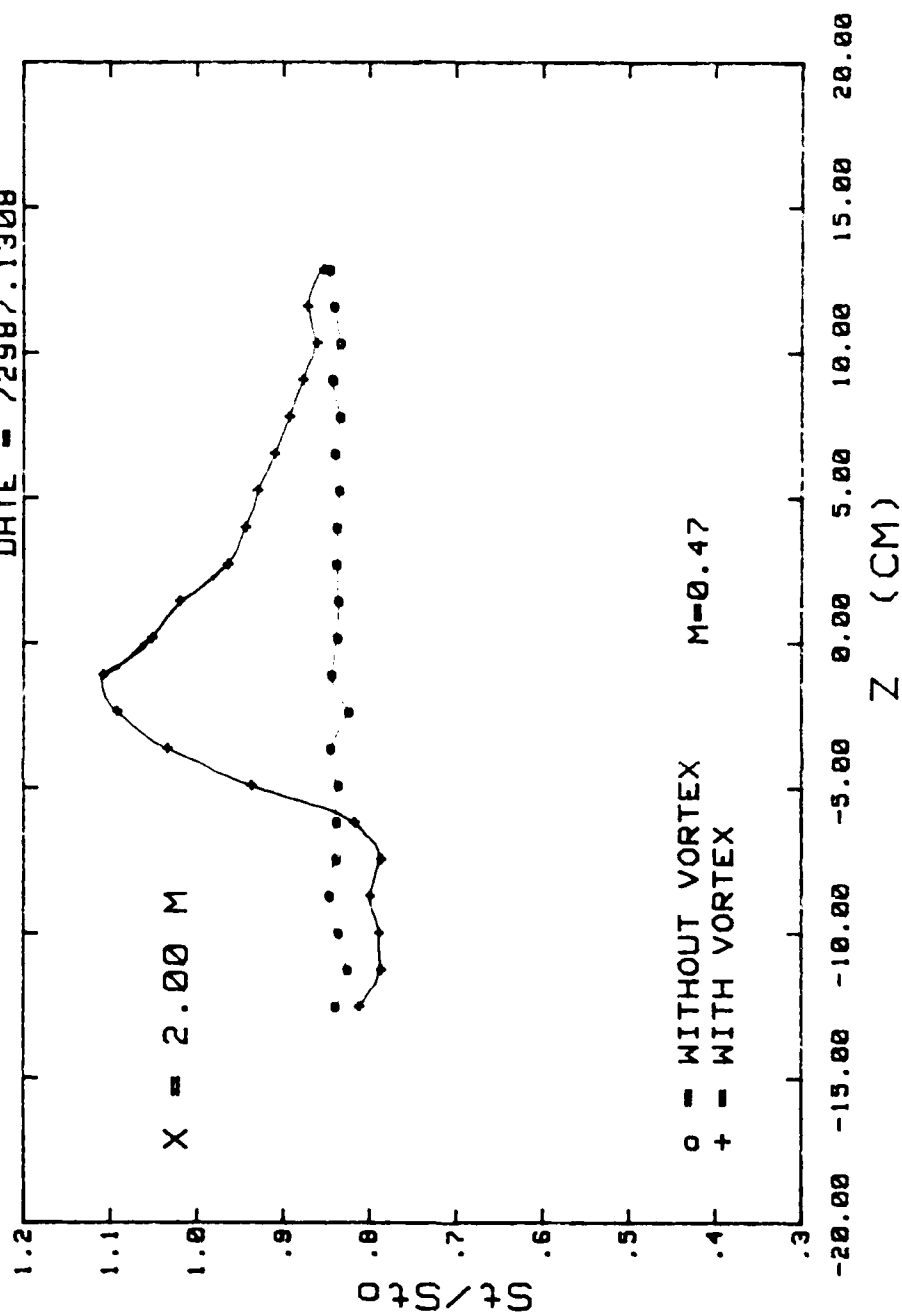
DATE - 72987.1308



FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79cm  
 Fig. 43e. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 72987.1308

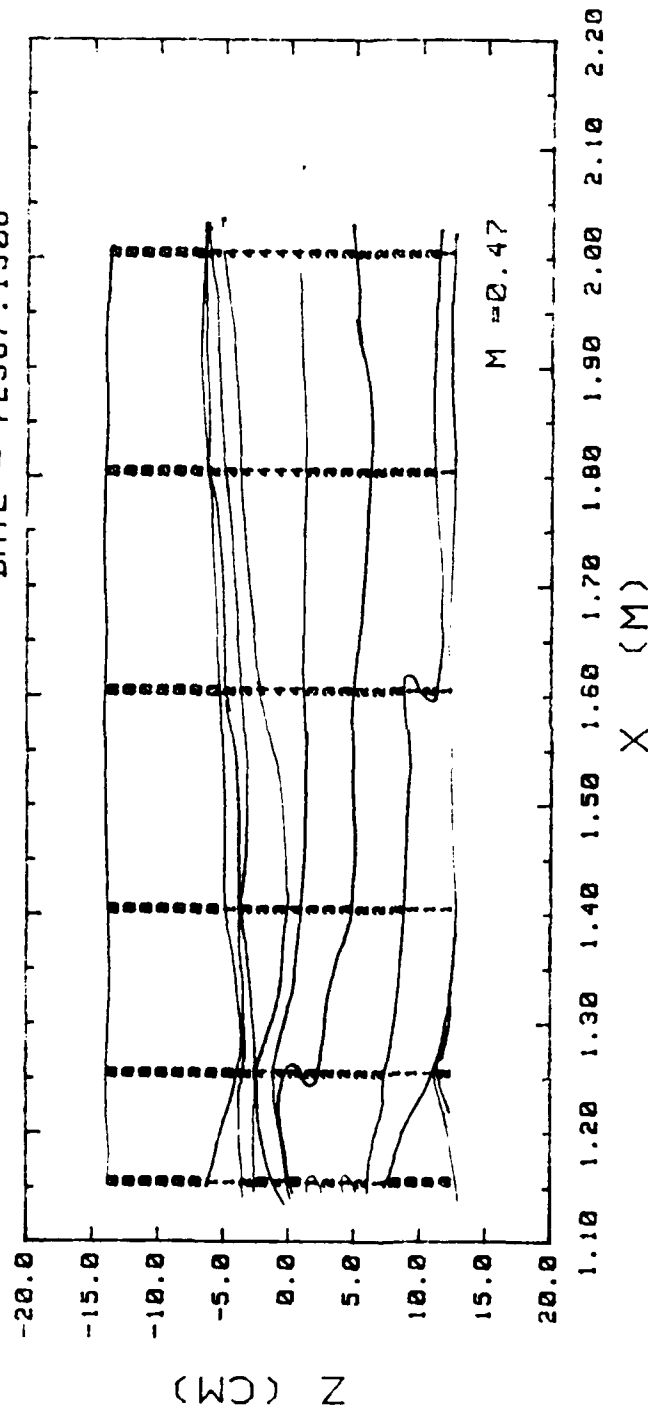


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 43f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 72987.1308



St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 4.79 cm  
Fig. 44. Surface Contour.

# STANTON NUMBER RATIOS

DATE = 72987.1345

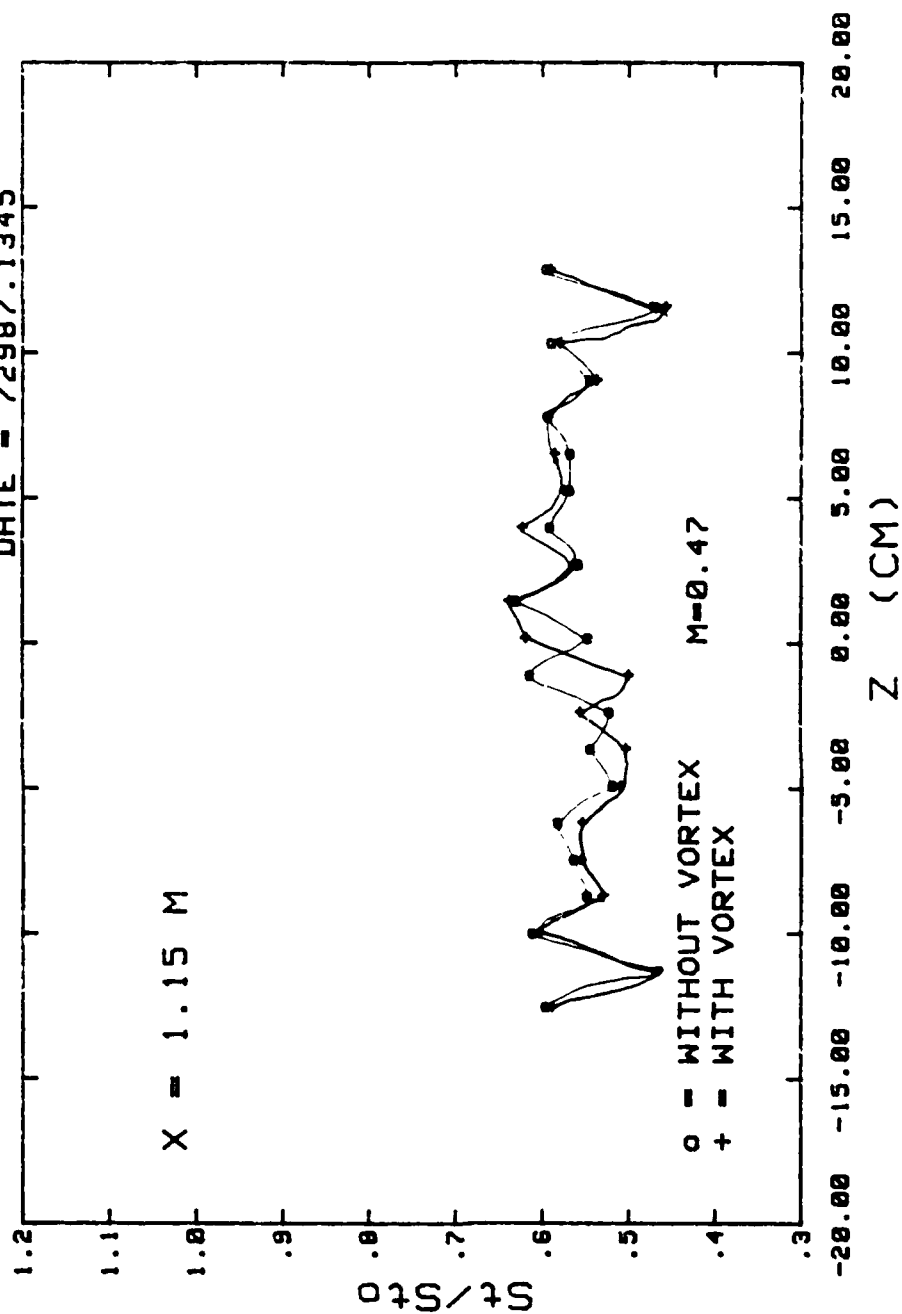
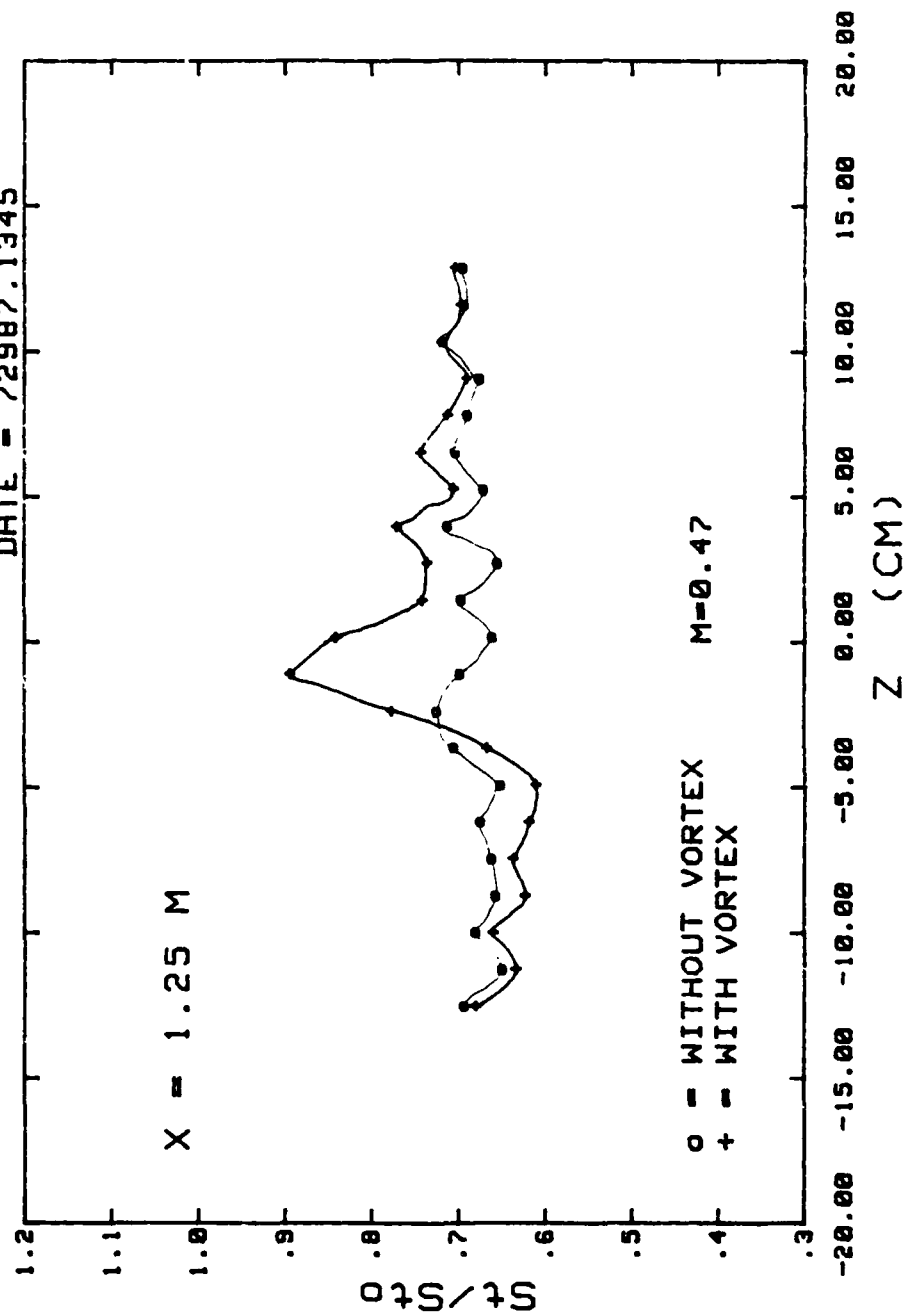


Fig. 45a. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 72987.1345

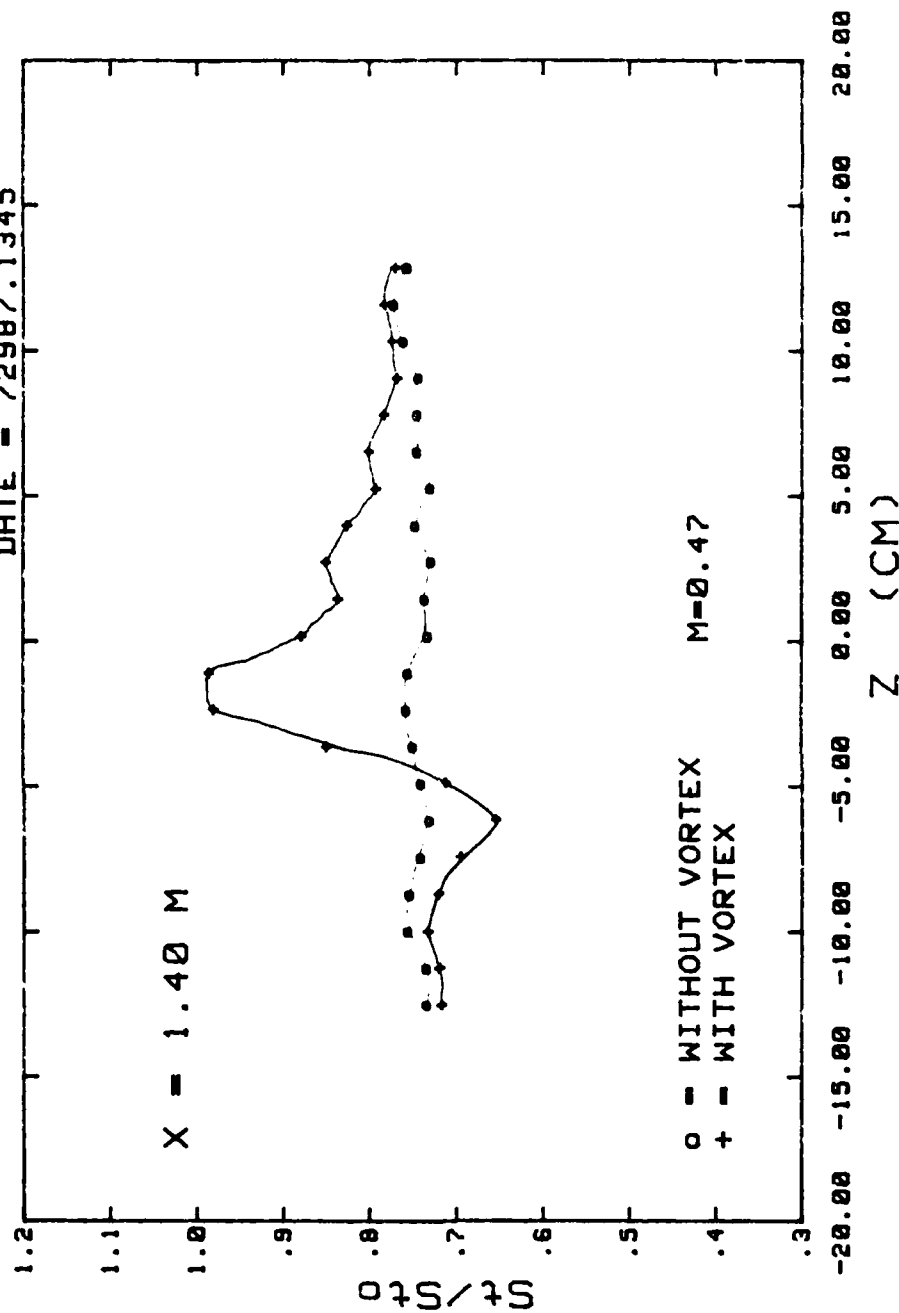


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 3.52 cm

Fig. 45b. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 72987.1345

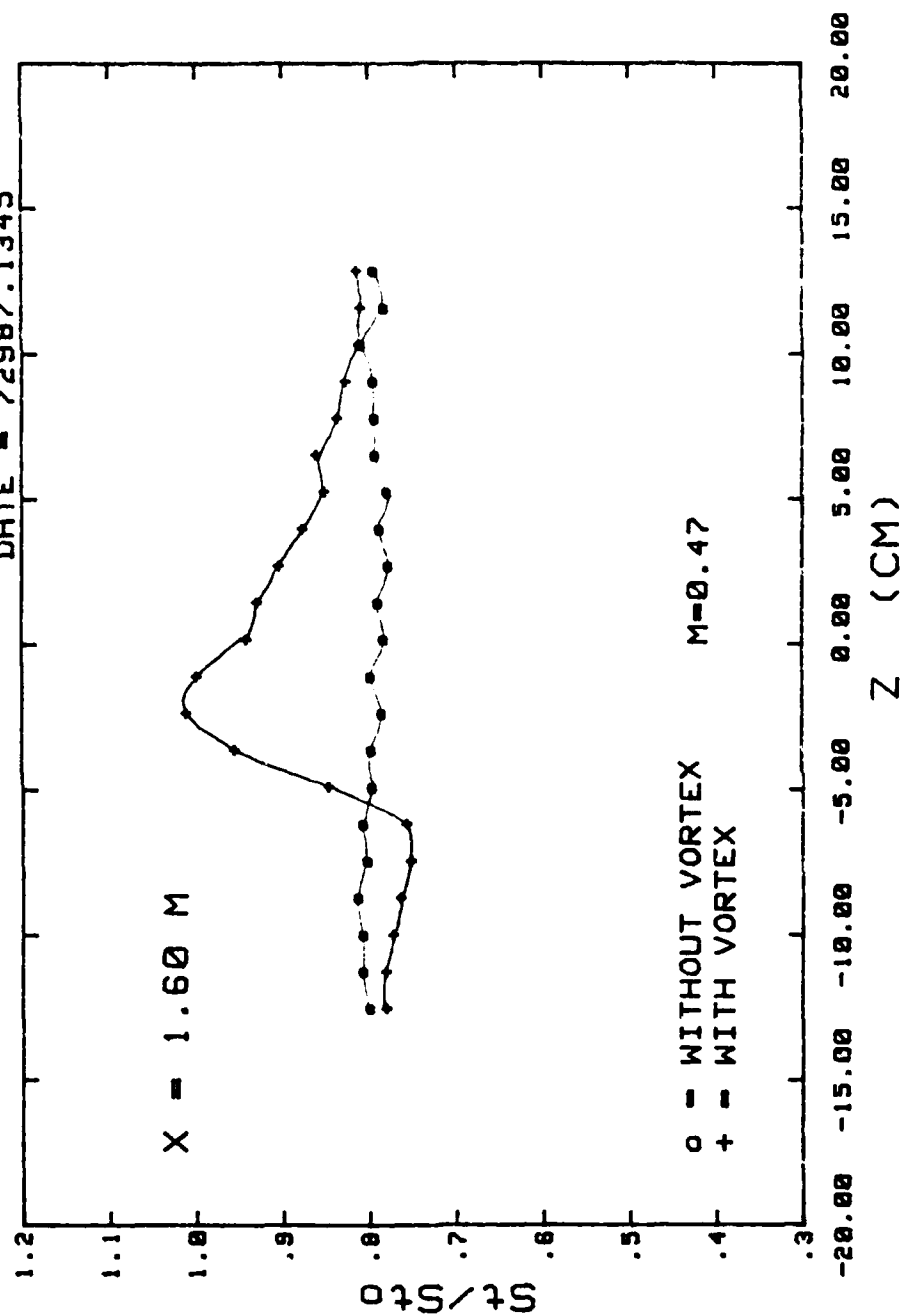


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 3.52 cm  
 Fig. 45c. Sparwise Variations of Stanton Number Ratios.



# STANTON NUMBER RATIOS

DATE - 72987.1345

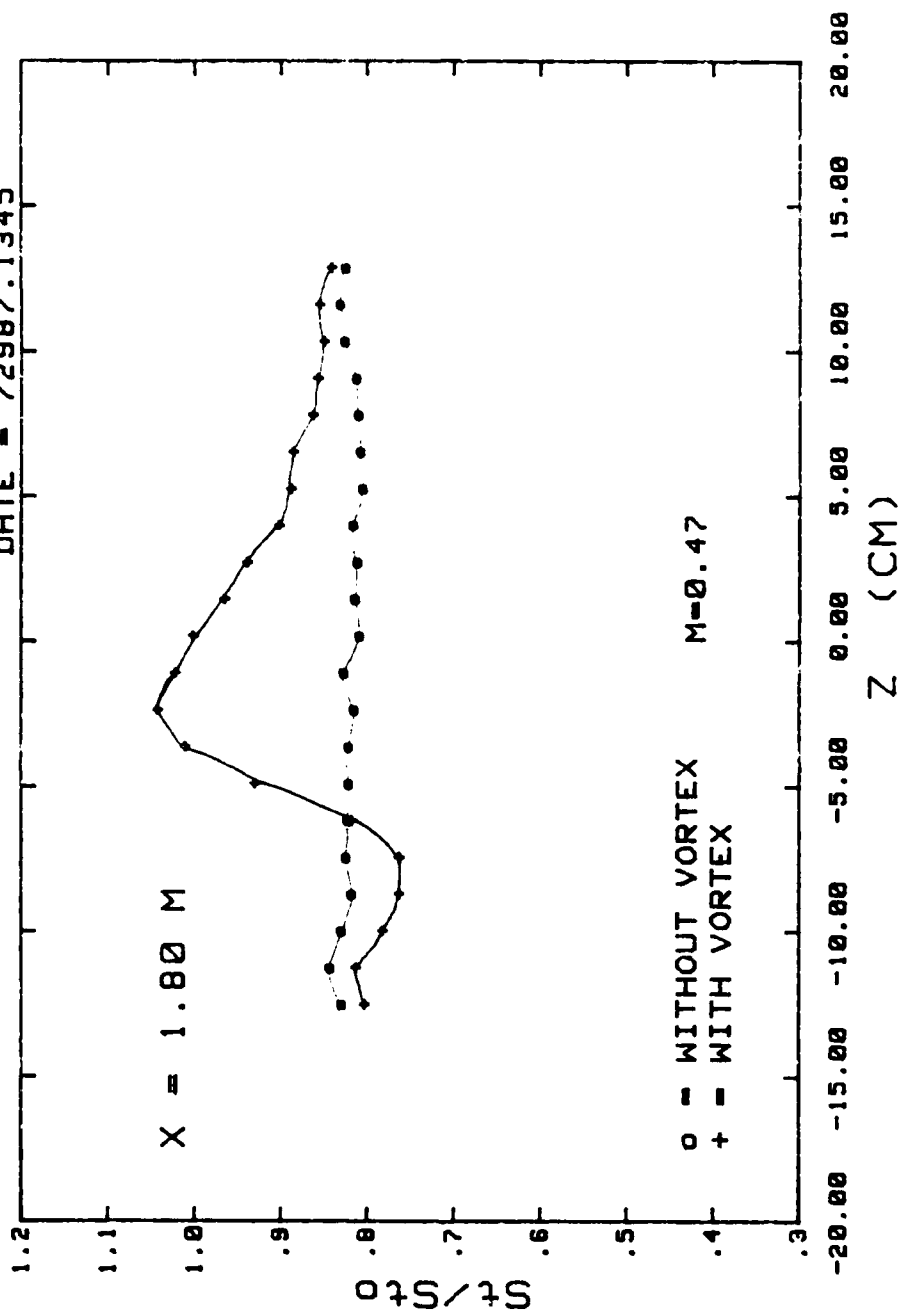


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 3.52 cm

Fig. 45d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

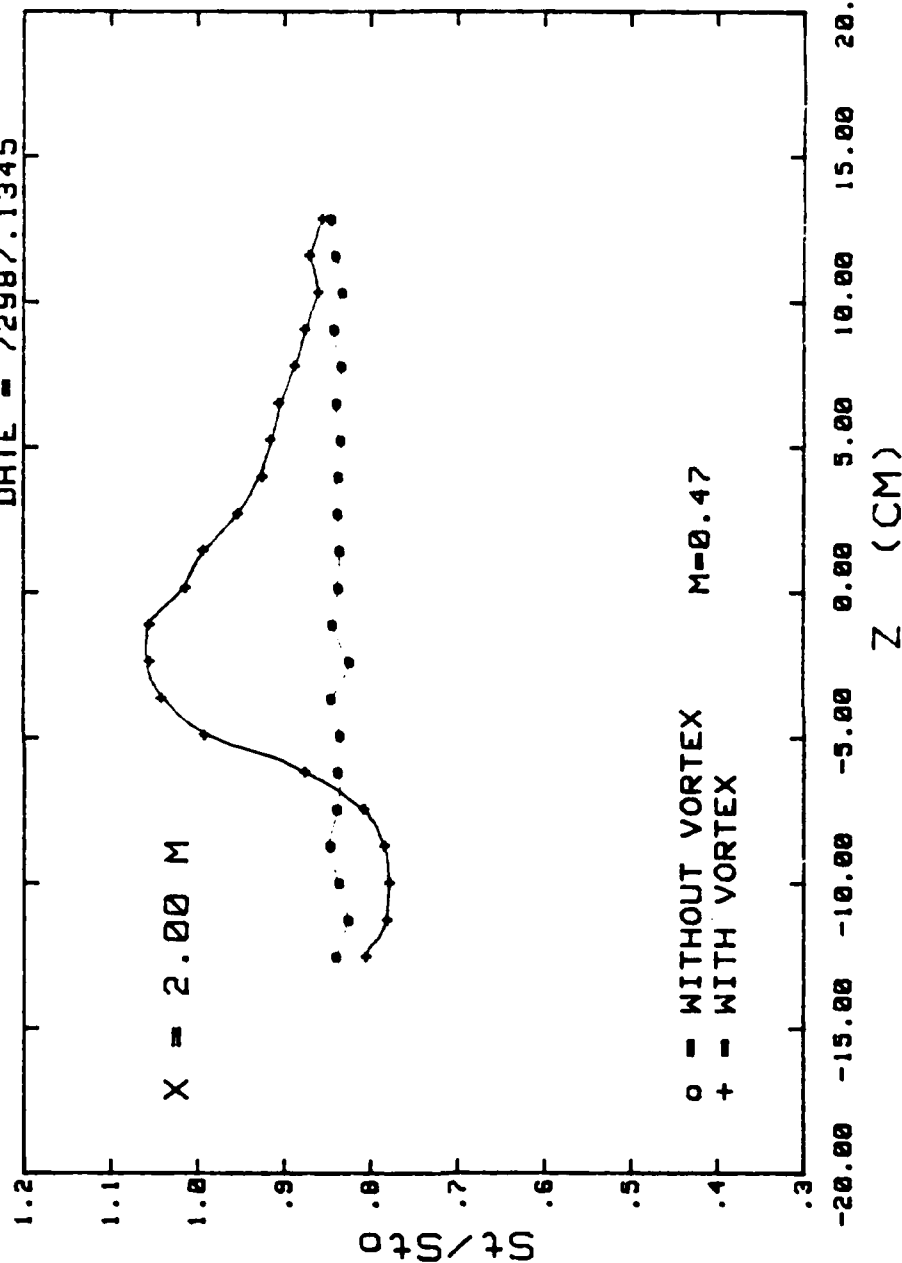
DATE = 72987.1345



FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 3.52 cm  
Fig. 45e. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 72987.1345

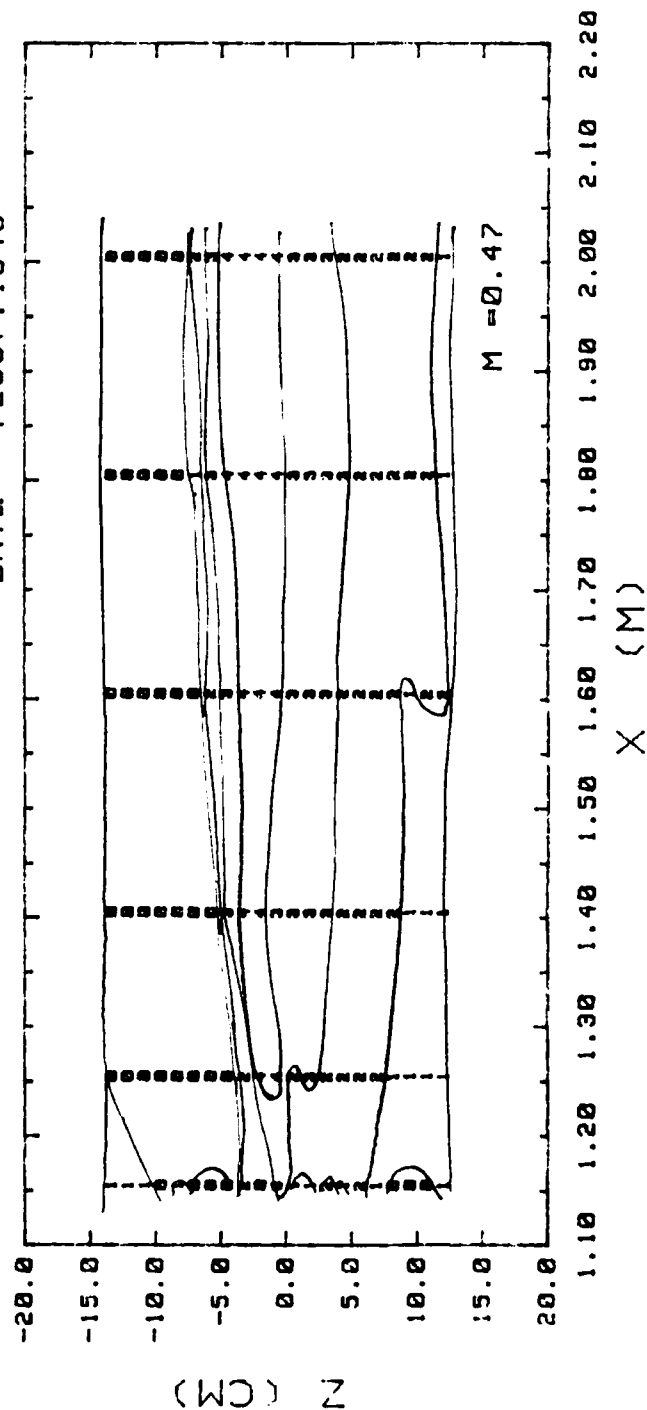


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 3.52 cm

Fig. 45f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 72987.1345



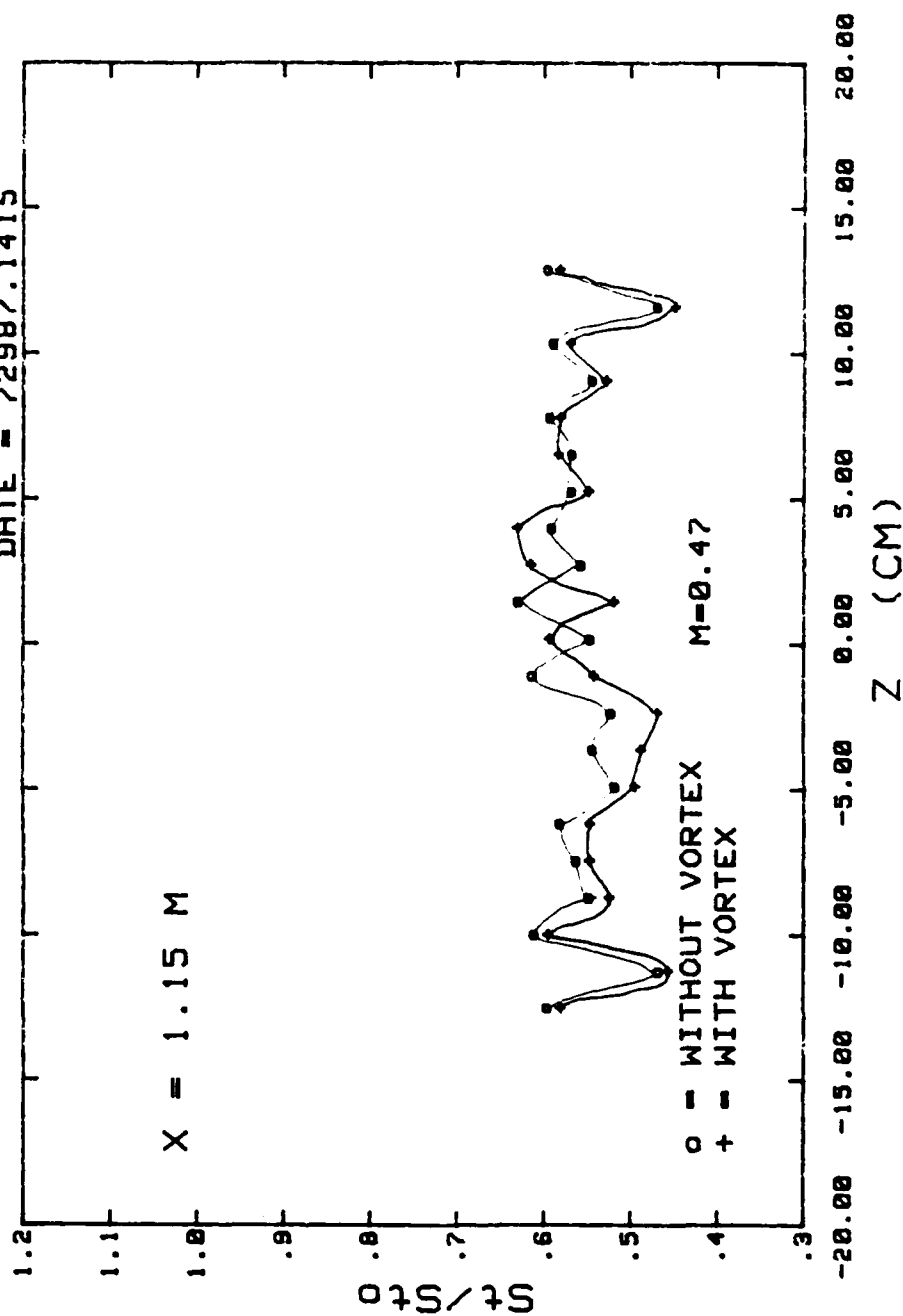
St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 3.52 cm

Fig. 46. Surface Contour.

# STANTON NUMBER RATIOS

DATE = 72987.1415

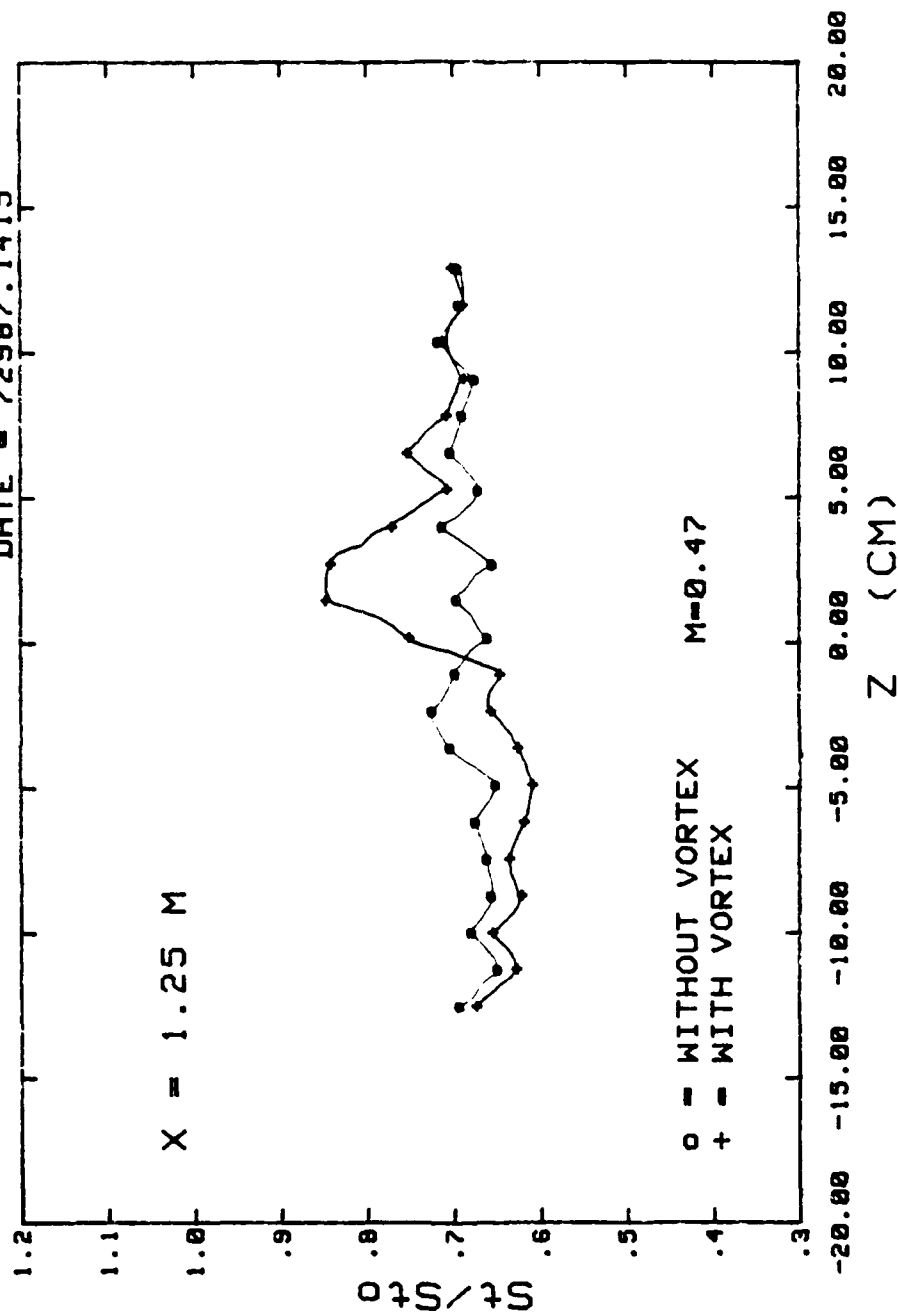


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 6.06 cm

Fig. 47a. Spanwise Variations of Stanton Number ratios.

# STANTON NUMBER RATIOS

DATE = 72987.1415

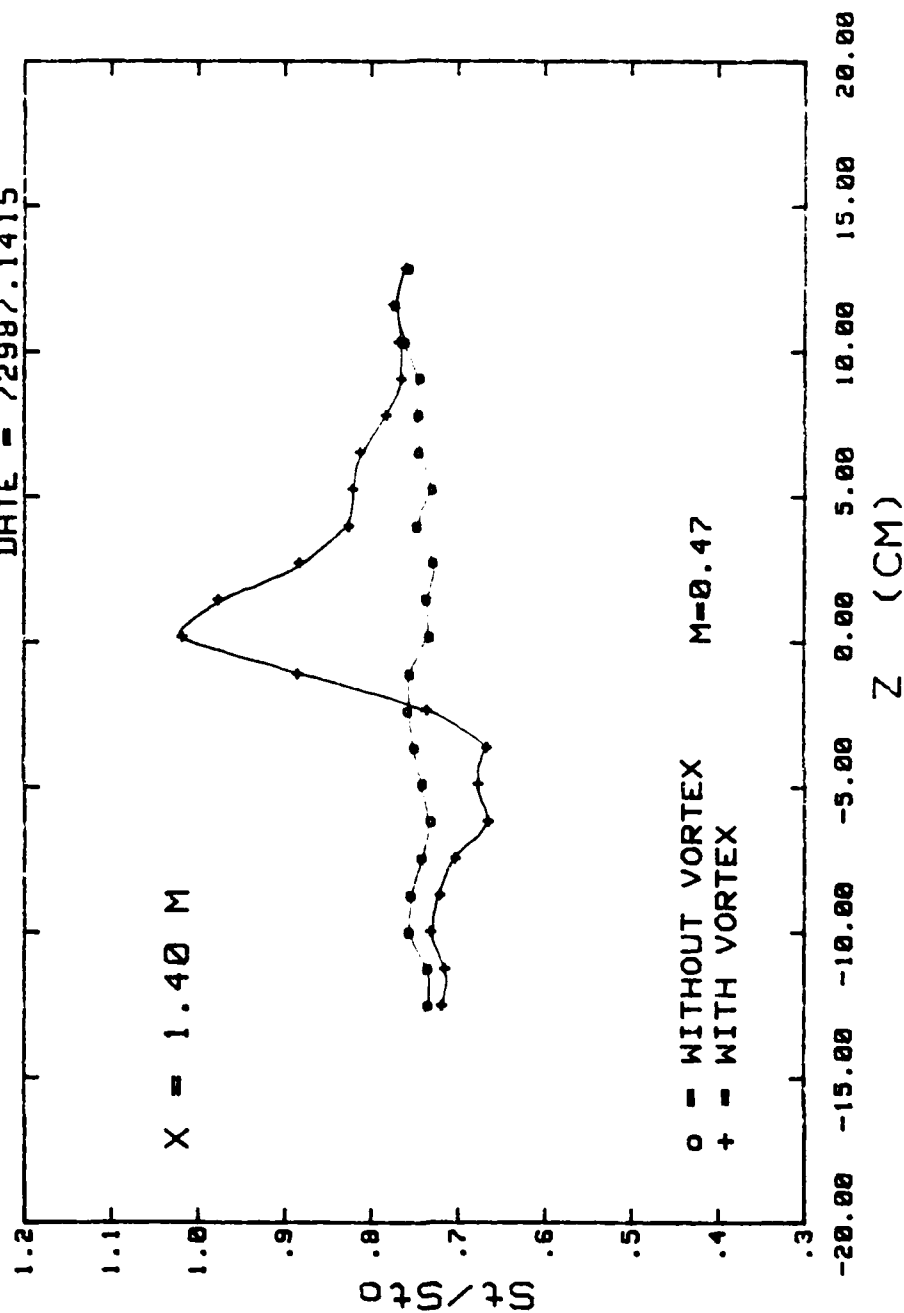


FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 6.06 CM

Fig. 47b. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

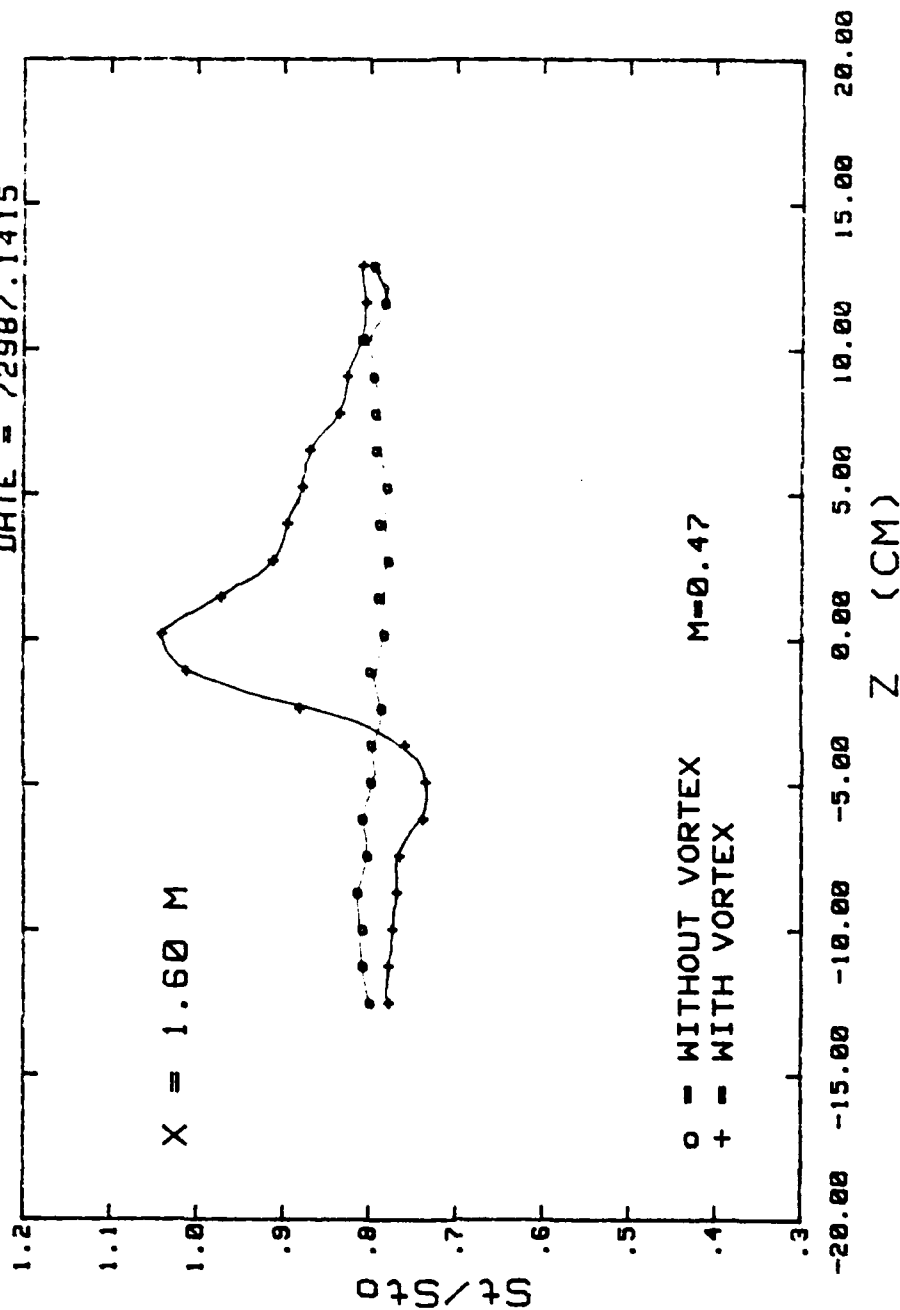
DATE - 72987.1415



FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 6.06 cm  
 Fig. 47c. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 72987.1415



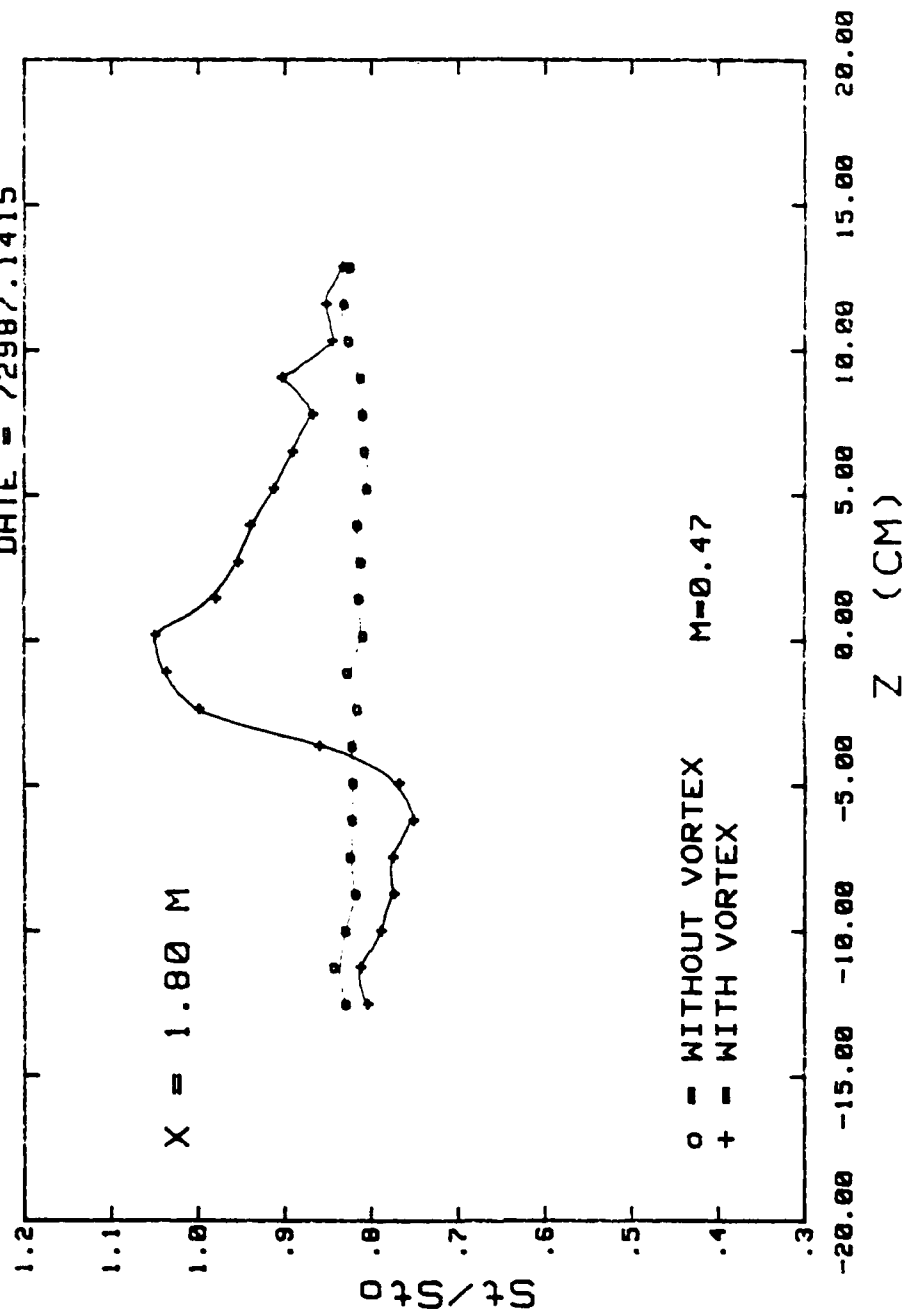
FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 6.06 cm

Fig. 47d. Spanwise Variations of Stanton Number Ratios.



# STANTON NUMBER RATIOS

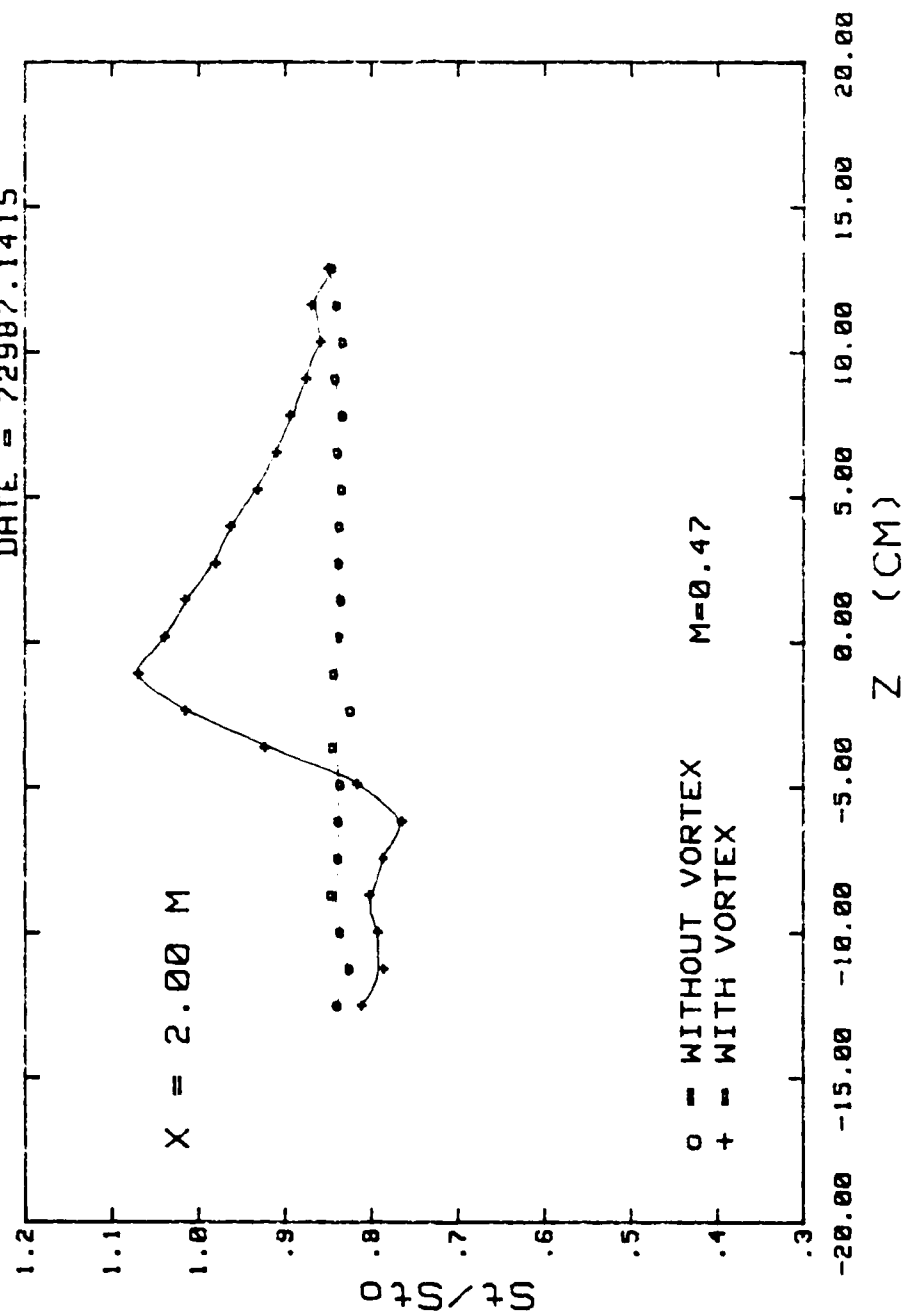
DATE = 72987.1415



FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 6.06 cm  
 Fig. 47d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

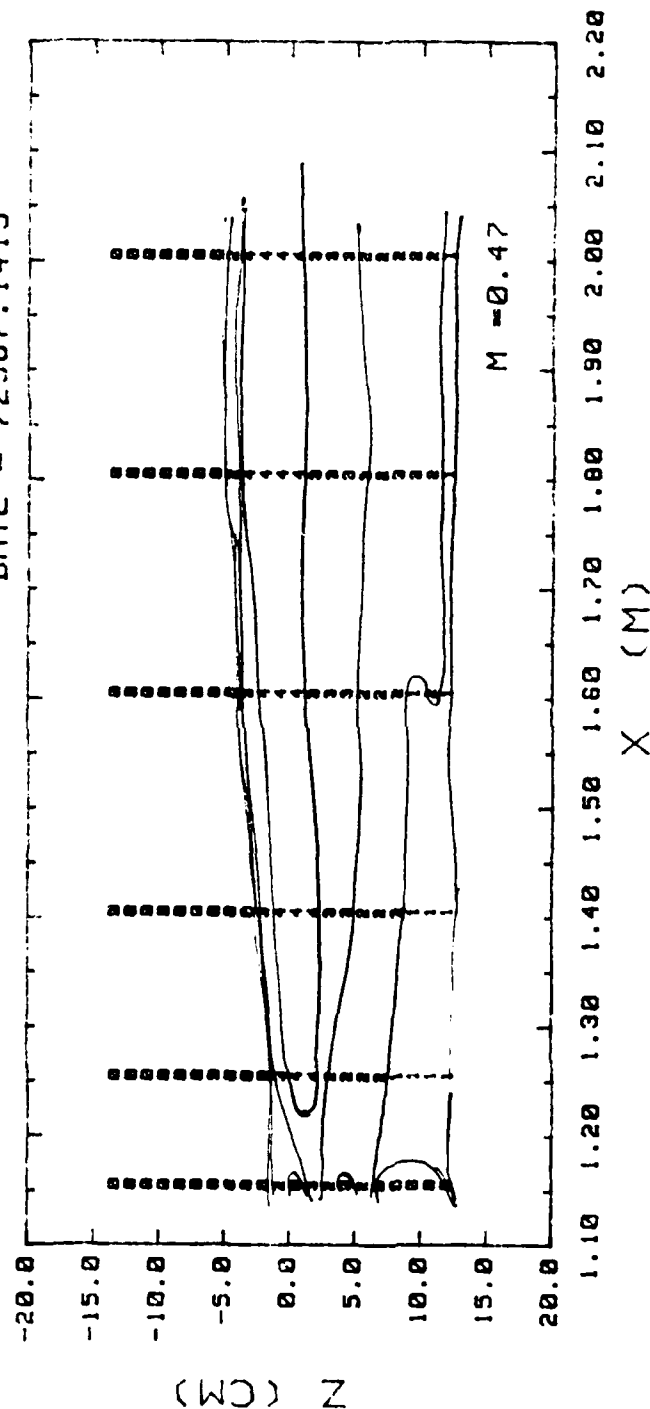
DATE = 72907.1415



FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. AT 6.06 cm  
 Fig. 47f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 72987.1415



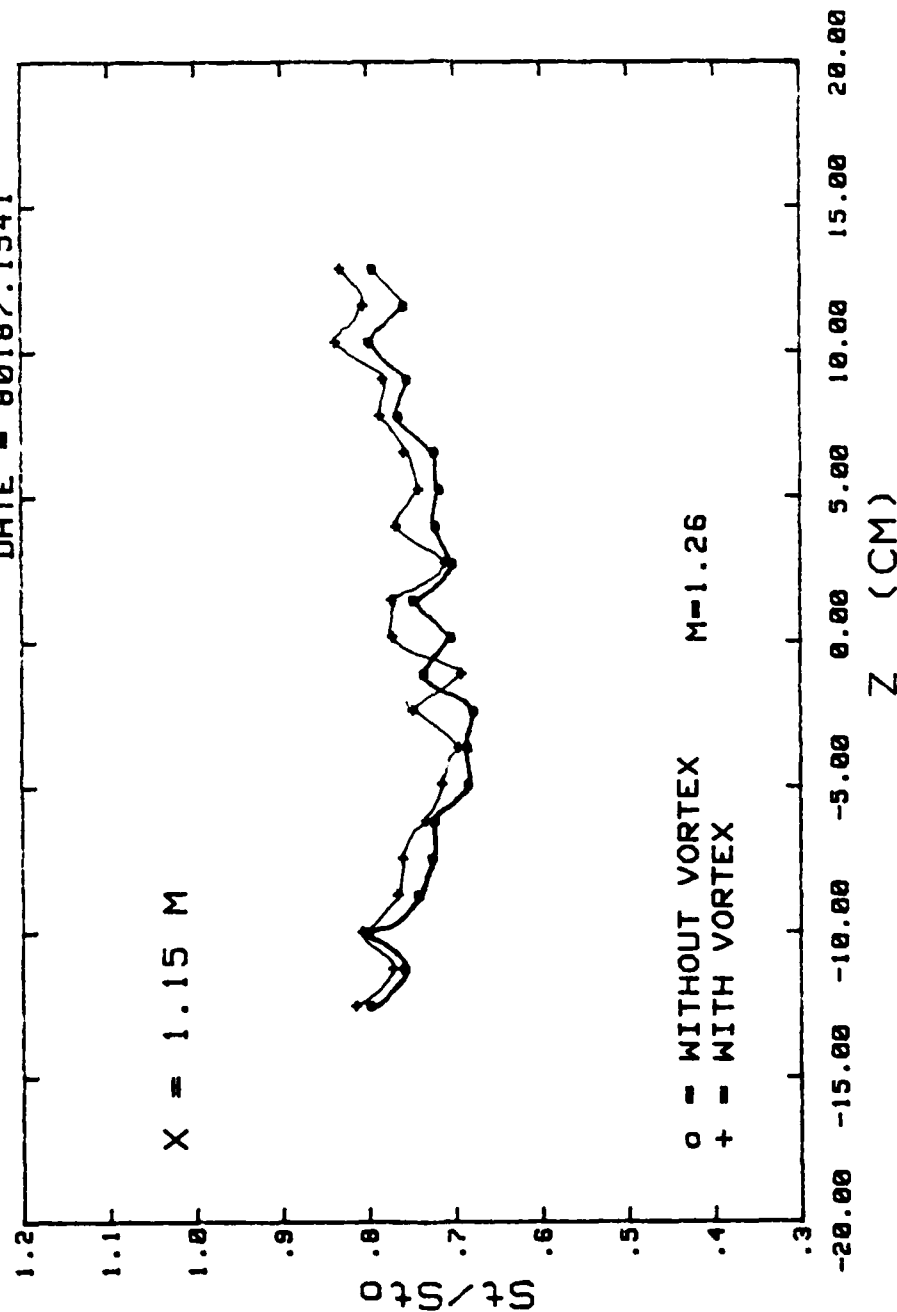
St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 15 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 6.06 cm

Fig. 48. Surface Contours

# STANTON NUMBER RATIOS

DATE - 00187.1541

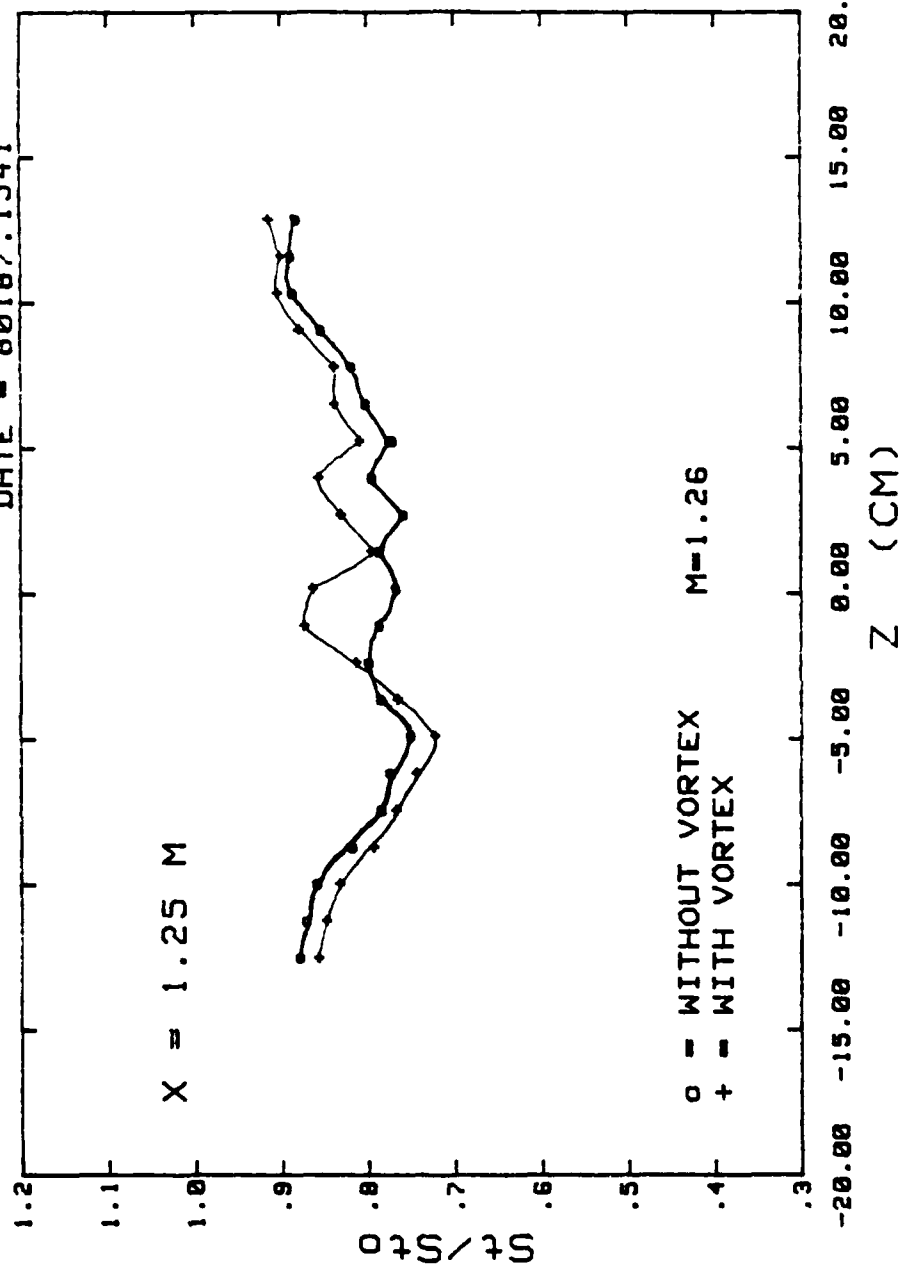


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 49a. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80187.1541

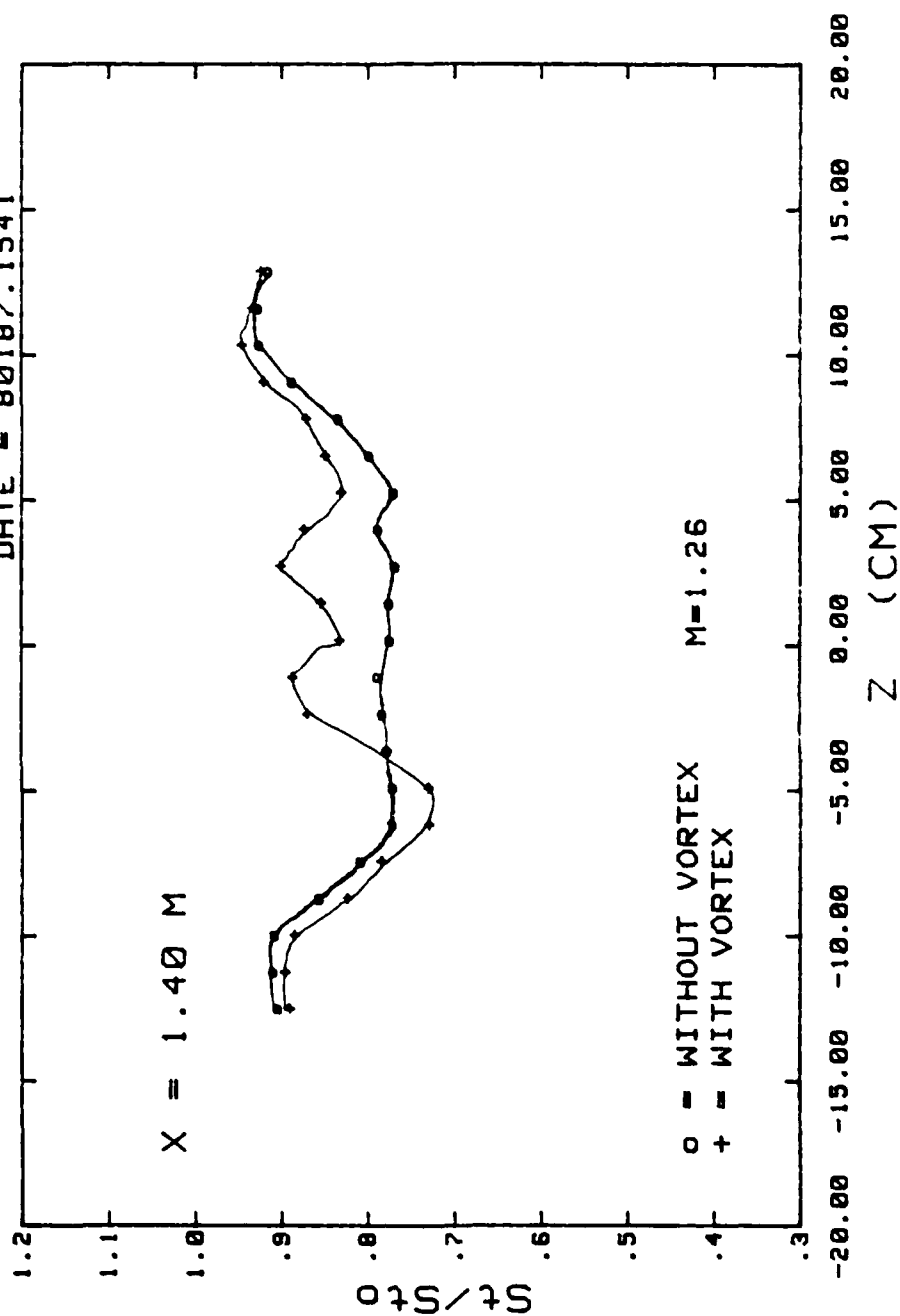


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 49b. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE - 80187.1541

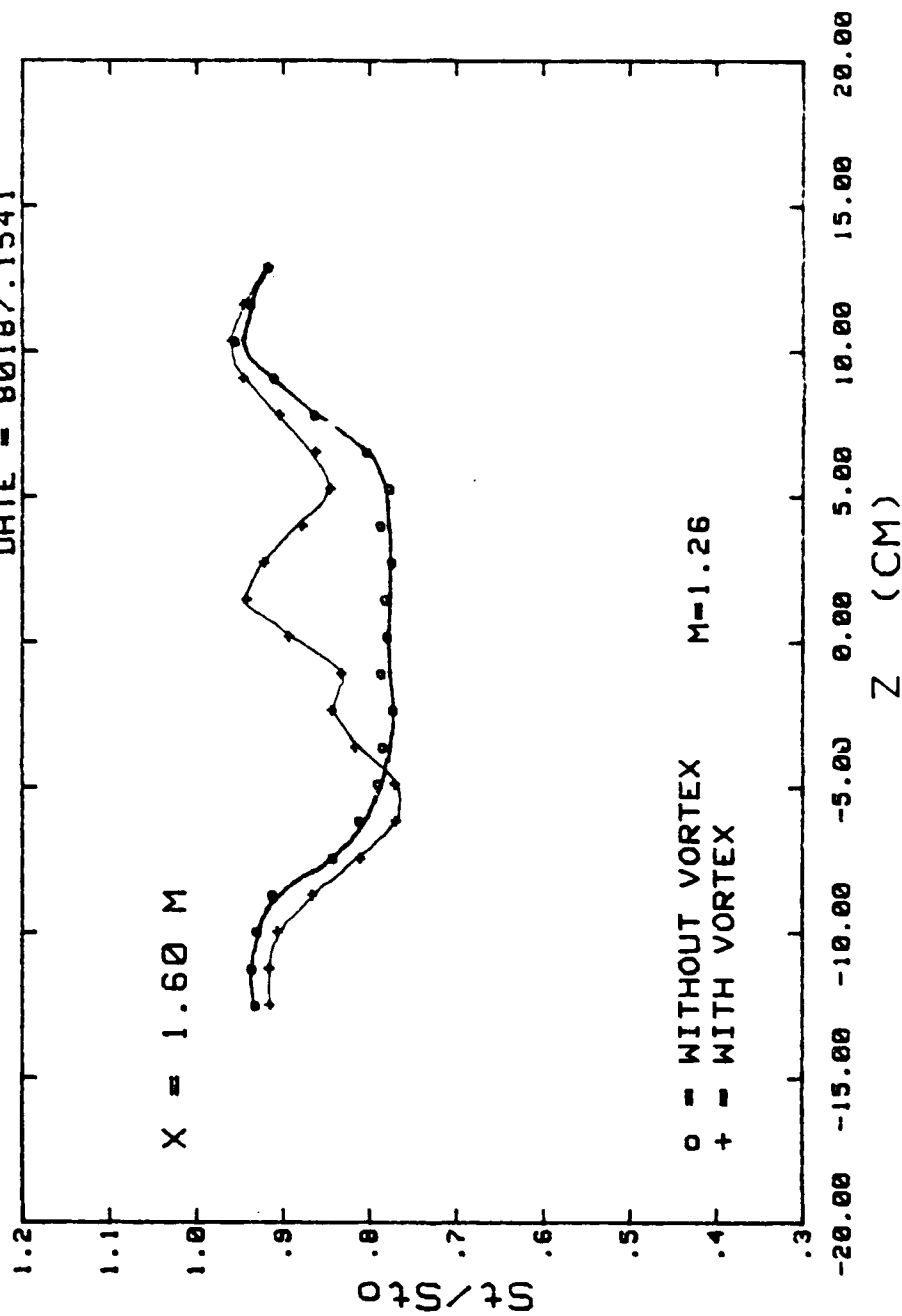


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 49c. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 80187.1541

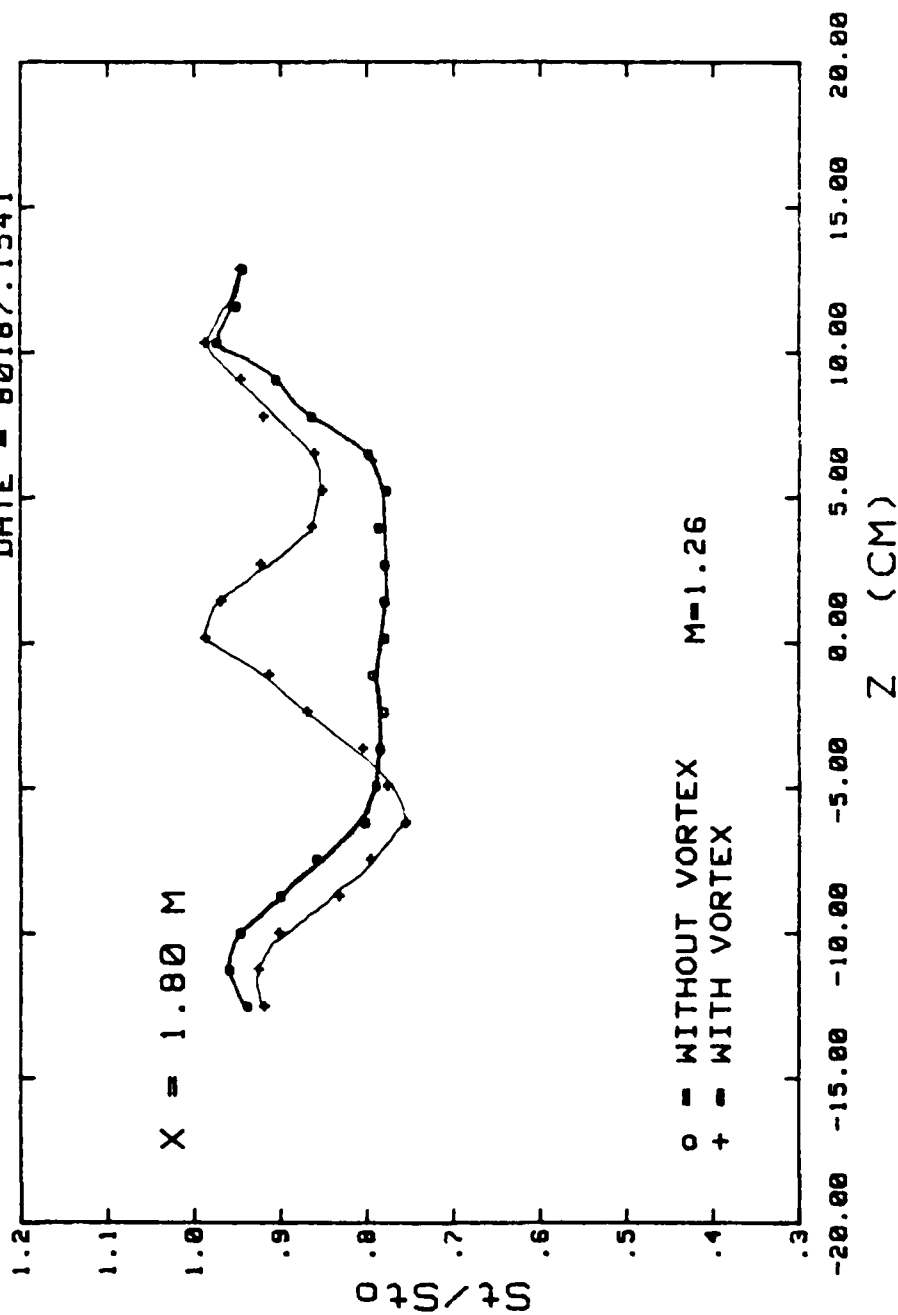


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 49d. Spanwise Variations of Stanton Number Ratios.

# STANTON NUMBER RATIOS

DATE = 80187.1541



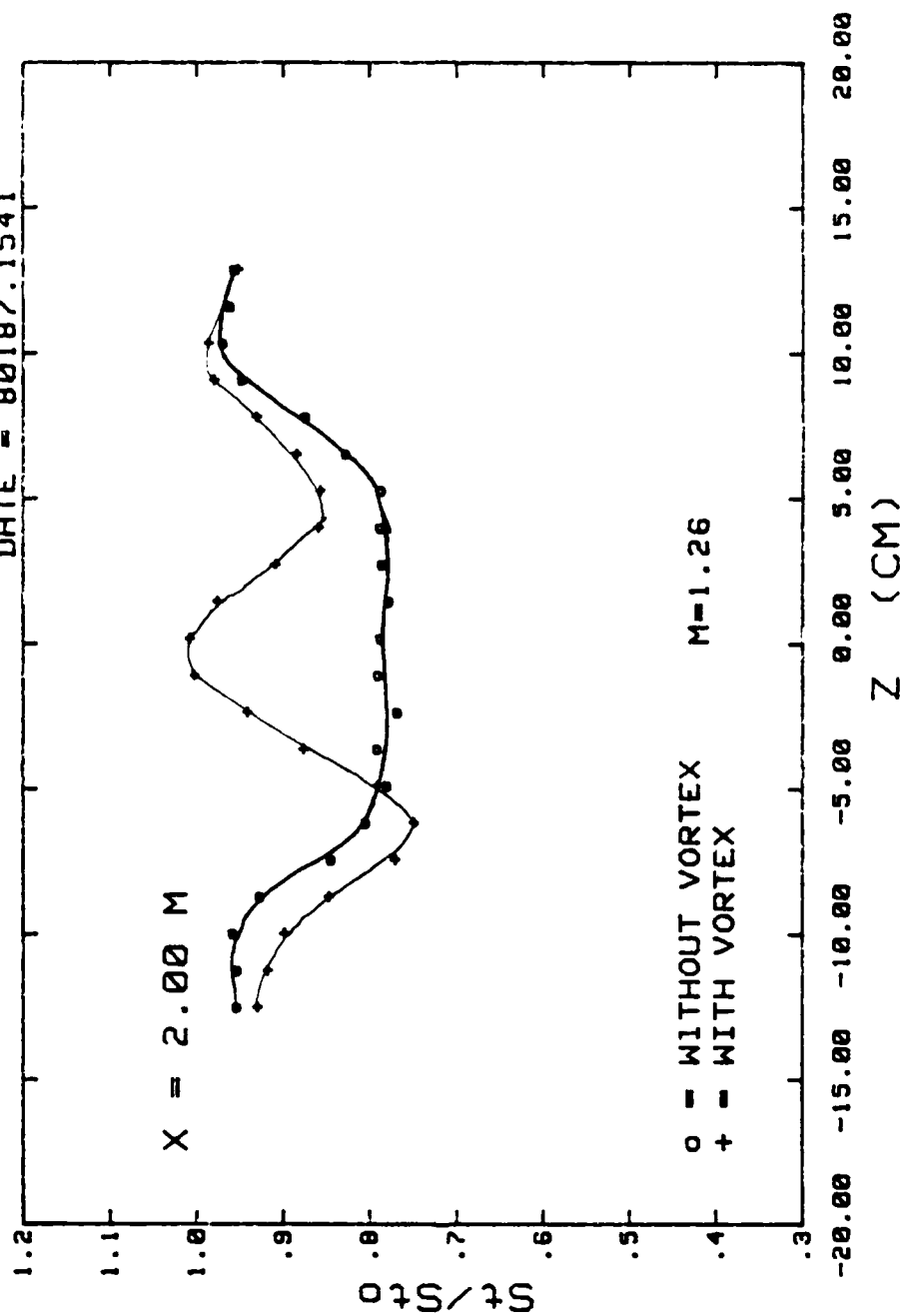
FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 49e. Spanwise Variations of Stanton Number Ratios.



# STANTON NUMBER RATIOS

DATE = 80187.1541

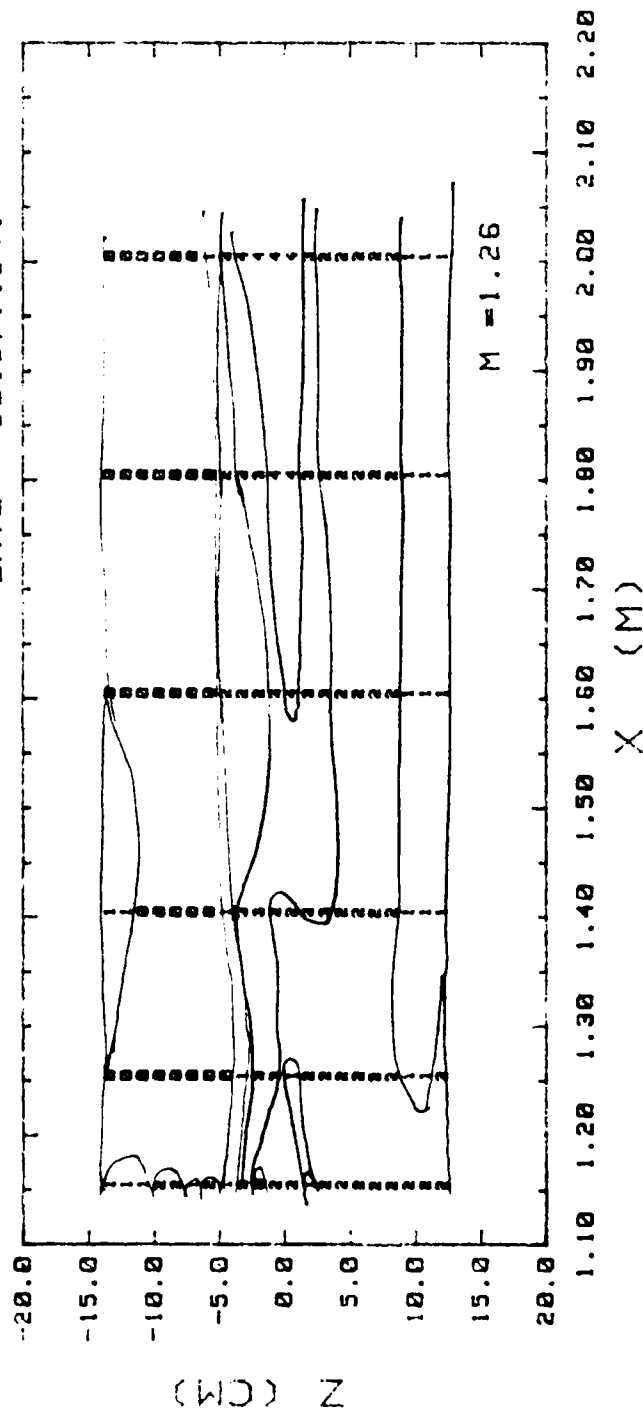


FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm

Fig. 49f. Spanwise Variations of Stanton Number Ratios.

# SURFACE CONTOURS

DATE = 80187.1541



St/Stf RANGES			
0	.900	.980	3 1.100 1.200
1	.980	1.020	4 1.200 1.300
2	1.020	1.100	

FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. #2 AT 4.79 cm

Fig. 50. Surface Contours.

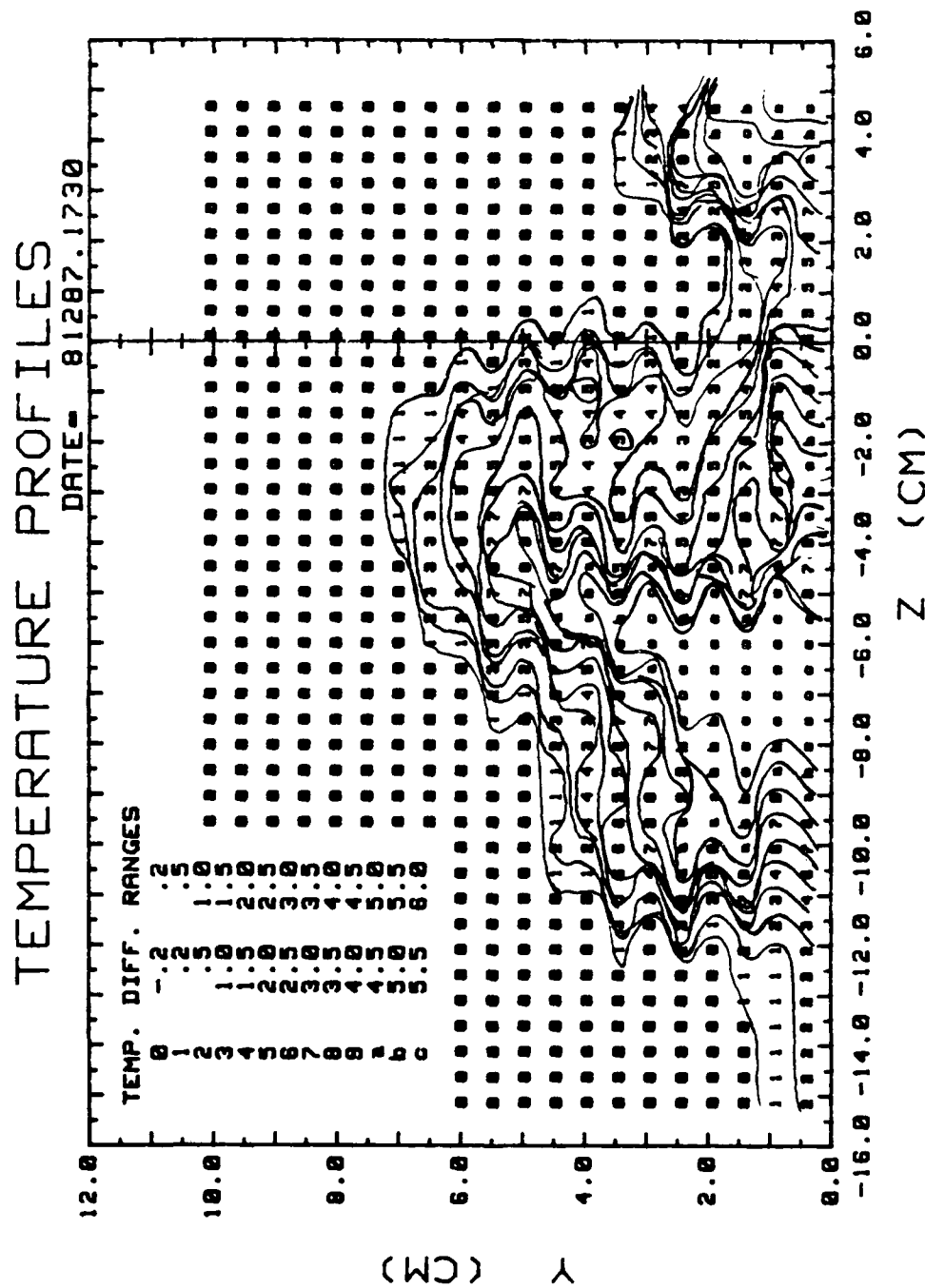
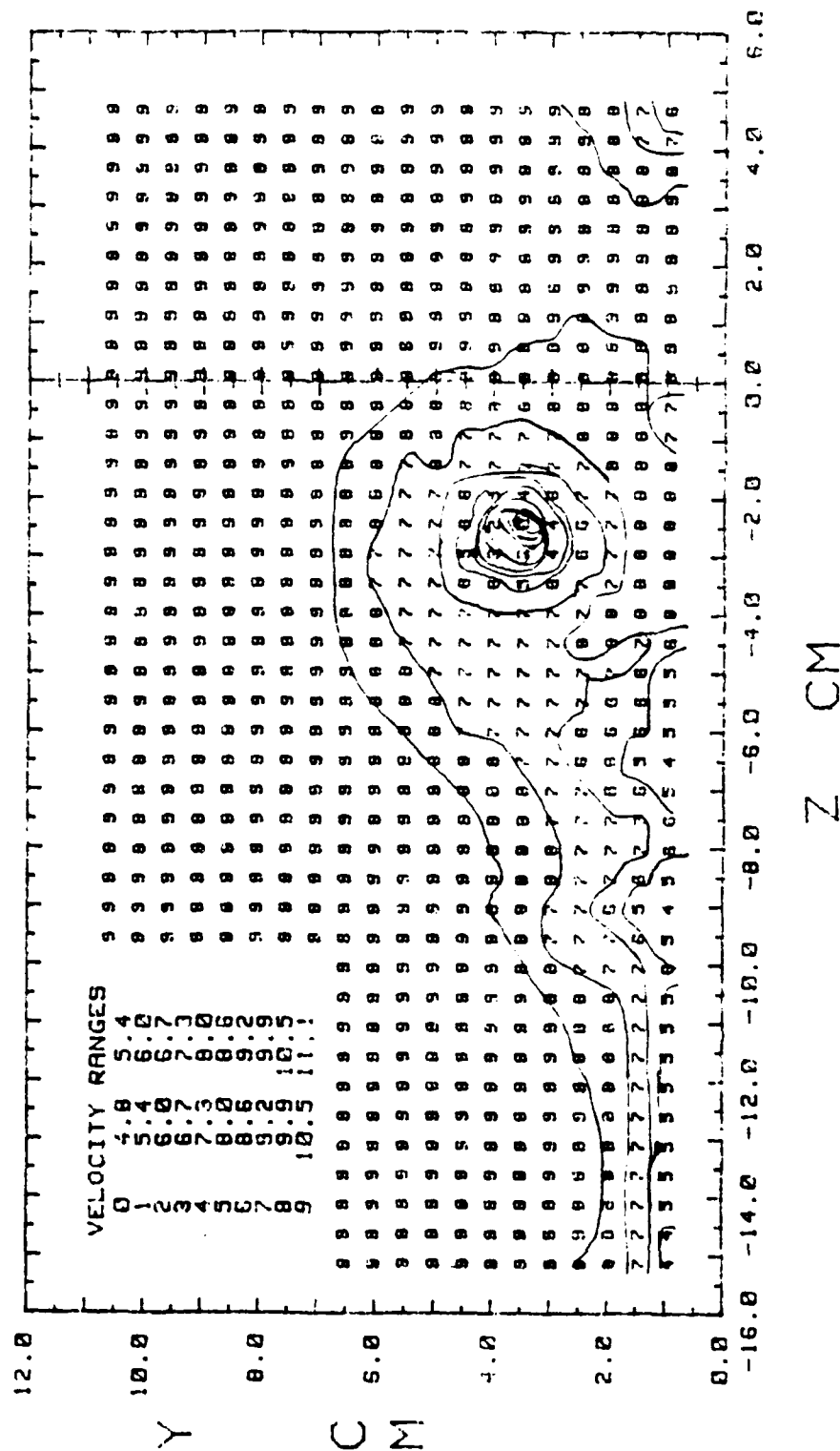


Fig. 51. EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=1.26$   
 $X=1.480$  M, UNHEATED PLATE, VORTEX GEN. AT 4.79 cm

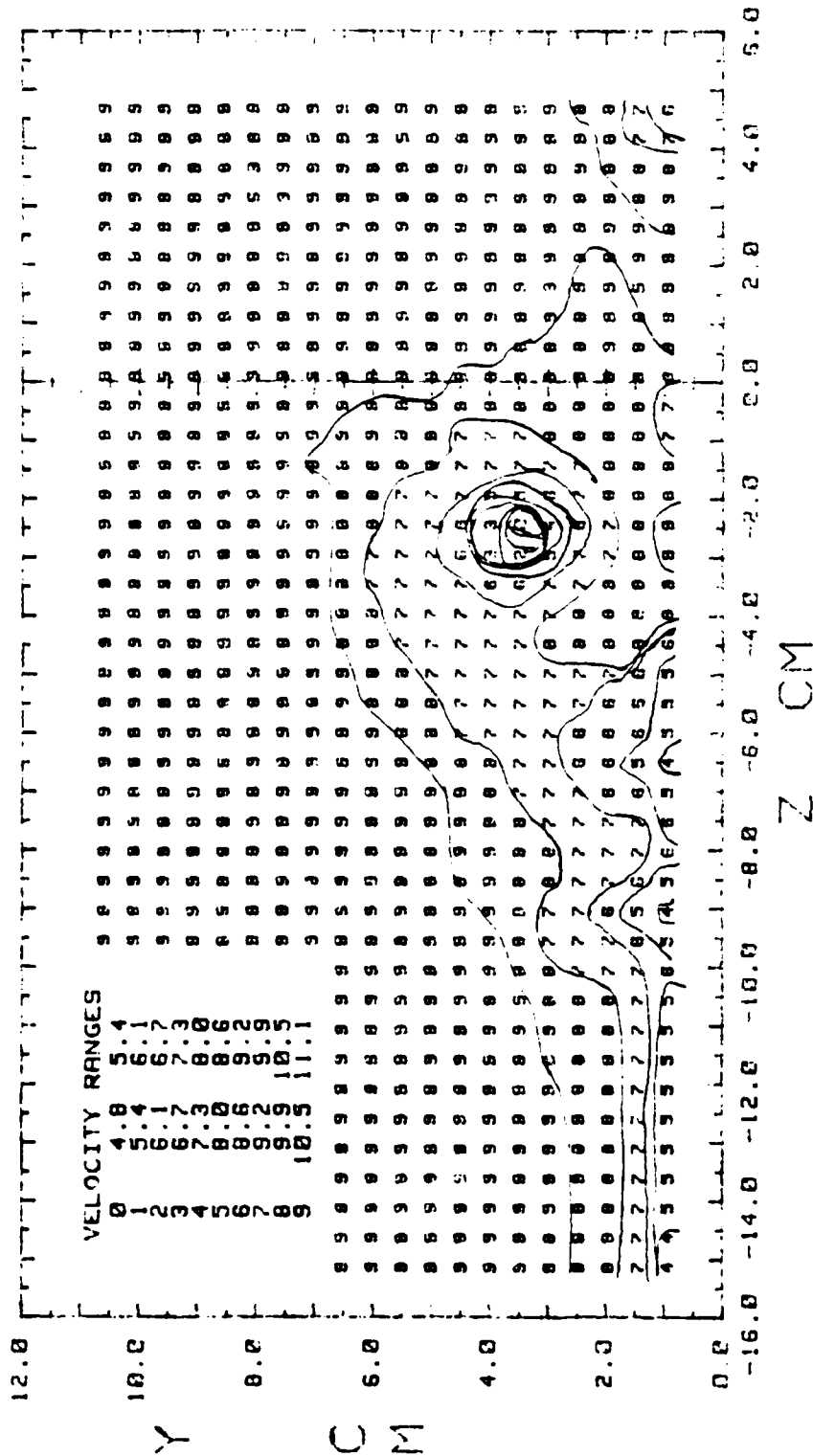
# STREAMWISE VELOCITY



EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=1.26$ , VORTEX GEN AT 4.79 cm

Fig. 52a. Streamwise Velocity Contour

# TOTAL VELOCITY



EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=1.25$   
VORTEX GEN. AT 4.79 cm

Fig. 52b. Total Velocity Contour.

# TOTAL PRESSURE

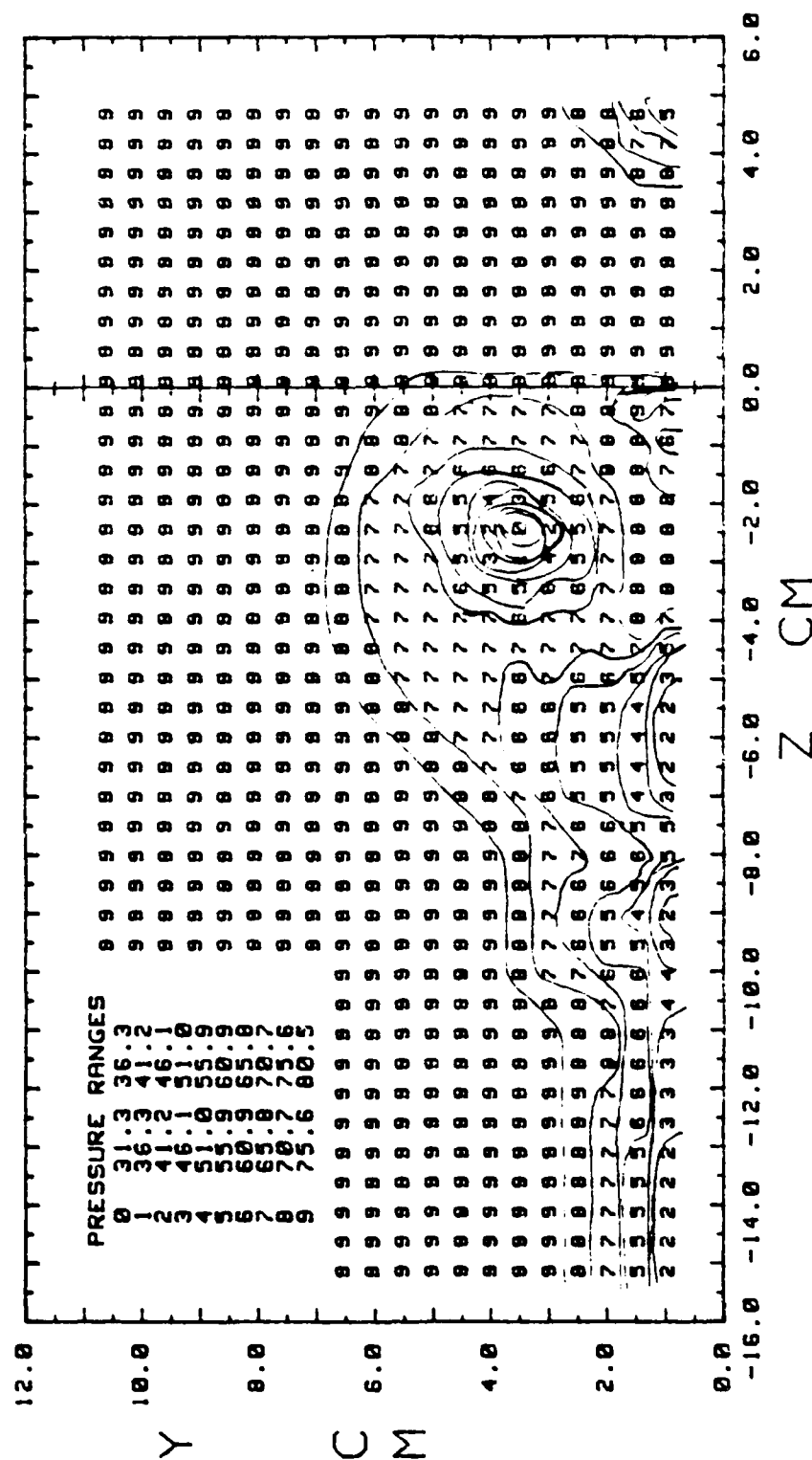
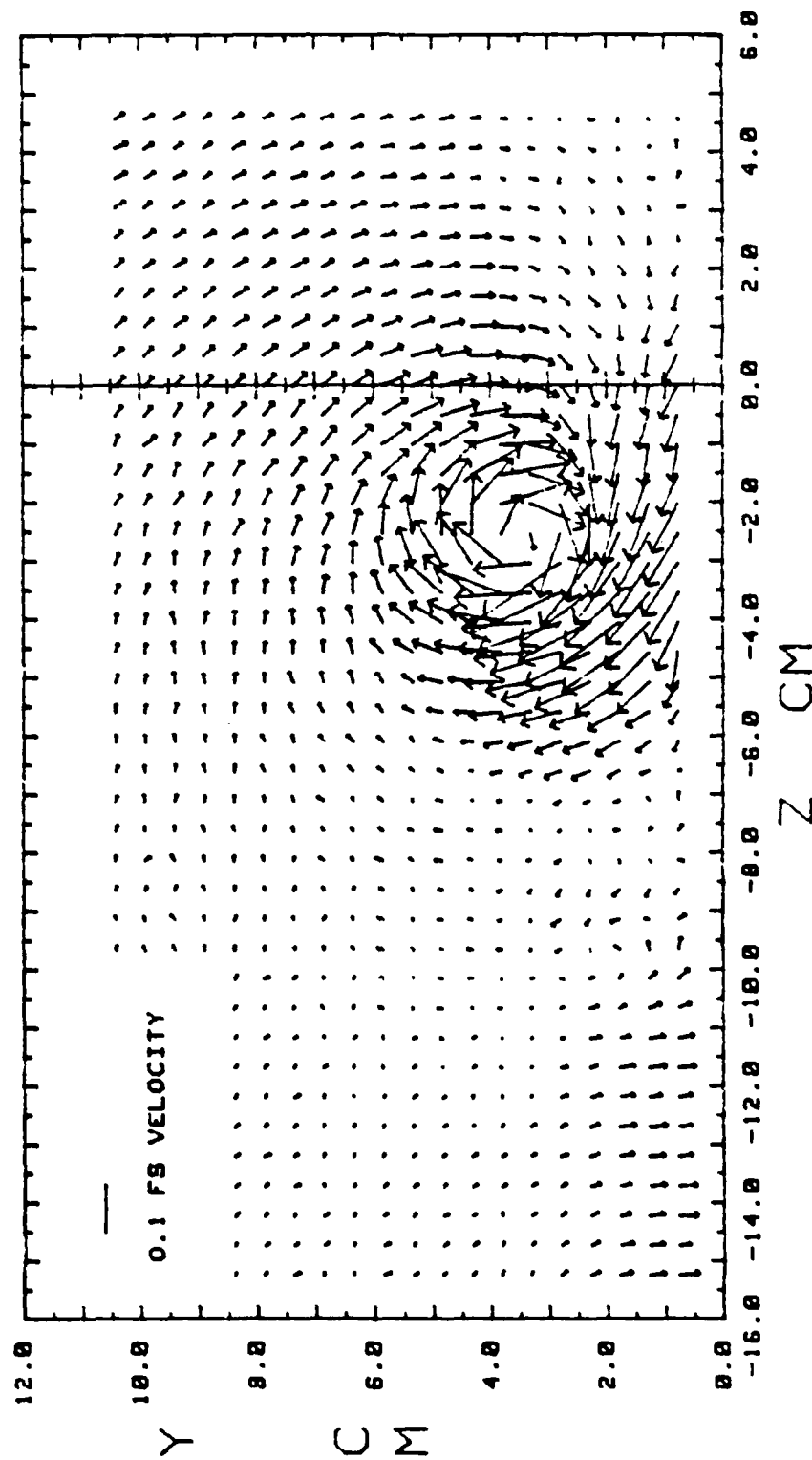


Fig. 52c. EMBEDDED VORTEX 10 M/S WITH FILM COOLING, M=1.26  
VORTEX GEN. AT 4.79 cm

# SECONDARY FLOW VECTORS



EMBEDDED VORTEX 10 M/S WITH FILM COOLING,  $M=1.26$ , VORTEX GEN. AT 4.79 cm

Fig. 52d. Secondary Flow Vectors.

# STREAMWISE VORTICITY

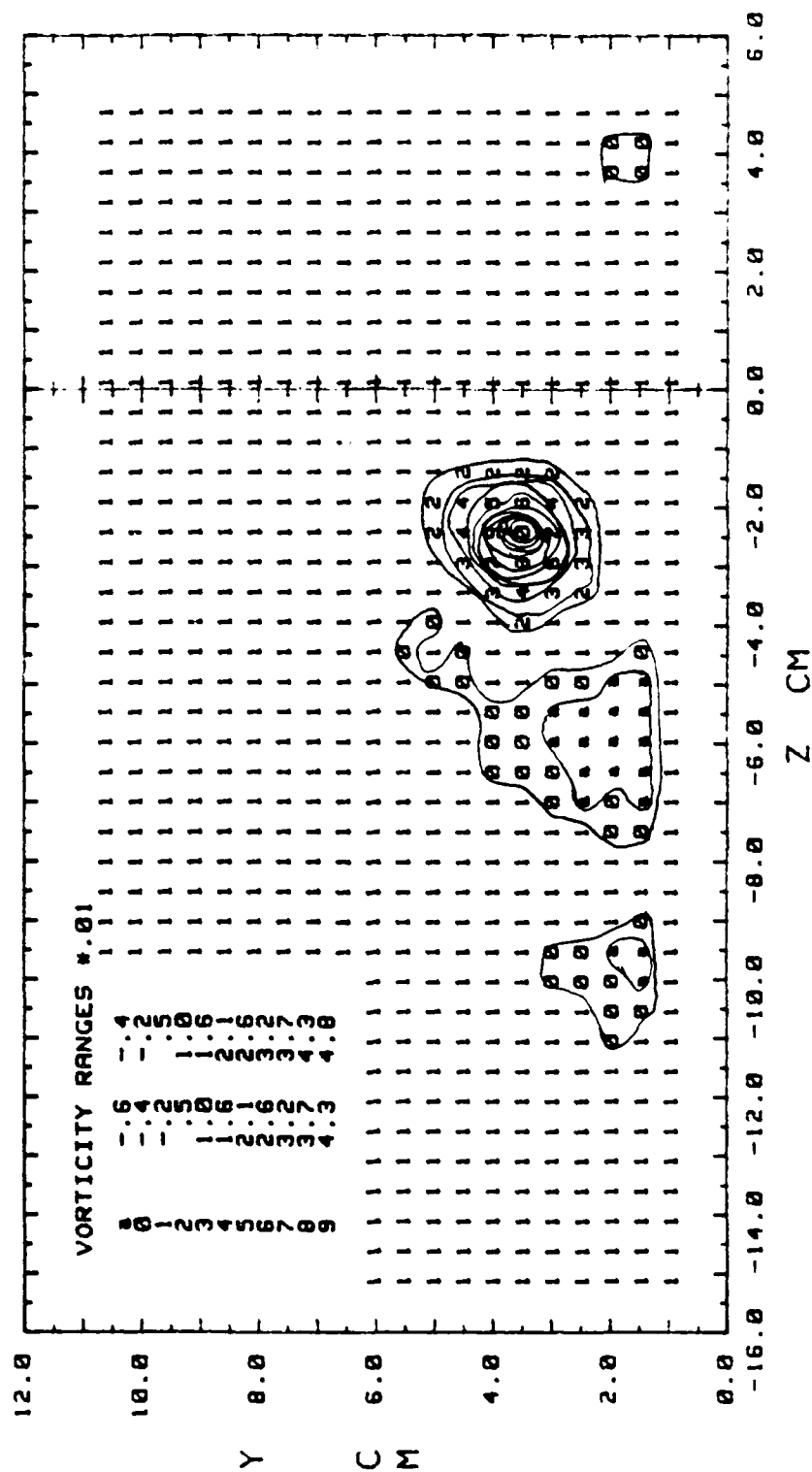


Fig. 52c. EMBEDDED VORTEX 10 M/S, VORTEX GEN. AT 4.79 cm  
FILM COOLING, M=1.26



## APPENDIX B

### UNCERTAINTY ANALYSIS

Uncertainty analysis was performed using the method proposed by Kline and McClintock [Ref. 19]. This is the root sum square method, where the uncertainty,  $\delta_F$ , of some function  $F$ , is a function of the independent variables  $X_n$ , according to the following expression:

$$\delta_F = \left( \sum_{i=1}^n \left( \frac{\partial F}{\partial X_i} \delta_i \right)^2 \right)^{1/2} \quad (\text{eqn. C.1})$$

All uncertainties are based on 95% confidence levels. To calculate the uncertainty of the Stanton number, it is necessary to calculate first the uncertainty in the heat transfer coefficient,  $h$ . The following independent variable uncertainties were determined:  $\delta_q = \pm 16 \text{ W/m}^2$ ,  $\delta T_w = \pm 0.5 \text{ }^\circ\text{C}$ ,  $\delta T_\infty = \pm 0.1 \text{ }^\circ\text{C}$ . Here, the uncertainty of heat loss by convection was based on a 5% error in radiation losses and 2.5% error in conduction losses. The uncertainty of  $T_w$  is higher than  $T_\infty$  due to higher uncertainty in the calculation of the contact resistance. From these parameters the uncertainty of  $h$  was determined to be 4.8% or approximately  $\pm 1.7 \text{ W/m}^2 \text{ }^\circ\text{C}$ , based on an  $h$  value of  $35 \text{ W/m}^2 \text{ }^\circ\text{C}$ .

To calculate the uncertainty of the Stanton number, besides the uncertainty of the heat transfer coefficient, the following independent variable uncertainties were determine:  $\delta \rho_\infty = \pm 0.01 \text{ kg/m}^3$ ,  $\delta U_\infty = \pm 0.5 \text{ m/s}$  and  $C_p =$

$\pm 1.0$  m/s. The uncertainty of  $C_p$  was based on the assumption of constant properties. From these parameters the uncertainty of the Stanton number was calculated to be  $\pm 6.04\%$ , or approximately  $1.87 \times 10^{-4}$  based on a typical Stanton number of 0.0035. The uncertainty of  $St/St_0$  is derived from the parameters already mentioned and was estimated to be  $\pm 7.1\%$  or  $\pm 0.05$  based on a  $St/St_0$  of 0.75.

To calculate the uncertainty of the blowing ratio,  $M$ , along the uncertainty values determined for  $U_\infty$  and  $\rho_\infty$ , the following independent variable uncertainties were:  $\delta U_{inj} = \pm 1.0$  m/s, and  $\delta p_{inj} = \pm 0.01$  g/cm<sup>2</sup>. The uncertainty of  $U_{inj}$  is higher than  $U_\infty$  due to higher uncertainty of the rotometer and the area of the injection holes, and the uncertainty of  $p_{inj}$  is also higher than  $p_\infty$  due to higher uncertainty in the estimation of  $T_{inj}$  from  $T_p$ . From these parameters the uncertainty of  $M$  was calculated to be  $\pm 8.4\%$  or about  $\pm 0.0078$  for a  $M$  value of 0.98.

## APPENDIX C

### SOFTWARE

The following programs are listed:

- ENSRB : energy balance estimation for conduction losses
- STANFC1 : heat transfer program to acquire thermocouple readings from DAS, and store information in data files in floppy disk
- STANFC2 : heat transfer program to calculate Stanton numbers for all flow conditions
- ACQTPRO : heat transfer program to acquire temperatures from automatic traversing device for temperature surveys
- PLOTRUN : program to read a data file to plot temperature contours
- PTSTAV : programs read a data file to plot spanwise averaged Stanton numbers vs. Reynolds number
- PTSTLC : reads a data file to plot spanwise local heat transfer coefficients
- PLSTRTIO : plots spanwise  $St/St_o$  for film cooling only.
- PLSTRVOR: plots spanwise variations of  $St/St_o$  for embedded vortex data only
- PLSTRVV: plots spanwise variations of  $St/St_o$  for film cooling only and  $St/St_o$  for film cooling and embedded vortex by rows.

SURFCONT: plots surface contours of  $St/St_f$

PLSTRFC : plots spanwise variations of local  $St/St_o$  for film  
cooling data only

Name of variables used are intended to be self explanatory

```

10 1 PROGRAM ENERGE
20 1
30 1THIS PROGRAM ACQUIRES MULTIPLE CHANEL THERMOCOUPLE DATA
40 1AND PERFORMS ENERGY BALANCE TO ESTIMATE CONDUCTION LOSSES
50 1LIGRANI/ORTIZ VERSION, JUNE 1988
60 1
70 DIM E(200),T(200)
80 1
90 1CHANNELS 0-79,100-146
100 100PPER CONSTANTAN THERMOCOUPLES
110 1
120 PRINTER IS 701
130 PRINT
140 PRINT "ENERGY BALANCE RESULTS"
150 PRINT "*****"
160 1 ENTER POWER IN (WATTS)
161 DISP "X HIT (CONTINUE)"
162 PAUSE
170 DISP "ENTER SUPPLY CURRENT IN AMPS, AND VOLTAGE IN VOLTS"
180 INPUT Amps,Volts
190 PRINT
200 PRINT "CURRENT =";Amps," VOLTS = ";Volts
210 PRINT
220 PRINT "TEMPERATURE RESULTS"
230 PRINT
240 Tave=0.
250 PRINT
260 FOR I=1 TO 19
270 OUTPUT 709;"AI";I;"VTI"
280 ENTER 709;X
290 E(I)=X*1000000.
300 T(I)=.018205+.025846+E(I)-.000000561+E(I)*E(I)
310 Tave=Tave+T(I)
320 PRINT USING 330;I,E(I),T(I)
330 IMAGE 000,3X,00000.0,3X,0000.00
340 NEXT I
350 PRINT "*****"
360 PRINT
370 PRINT
380 FOR I=40 TO 66
390 OUTPUT 709;"AI";I;"VTI"
400 ENTER 709;X
410 E(I)=X*1000000.
420 T(I)=.018205+.025846+E(I)-.000000561+E(I)*E(I)
430 Tave=Tave+T(I)
440 PRINT USING 450;I,E(I),T(I)
450 IMAGE 000,3X,00000.0,3X,0000.00
460 NEXT I
470 PRINT "*****"
480 PRINT
490 Tave=Tave/46.
500 PRINT "AVERAGE PLATE TEMP. MEASURED (DEG C) =";Tave

```

```

540 PRINT
550 GET T AMBIENT
560 OUTPUT 709;"AI";0;"VT1"
570 ENTER 709;X
580 E(0)=X*1000
590 T(0)=26.573+E(0)-1.936879+E(0)*E(0)+.99785+E(0)*E(0)*E(0)-.251277+E(0)*E(0)
    )*E(0)*E(0)
610 Tamb=T(0)
620 PRINT "AMBIENT TEMP. =";Tamb
630 PRINT
640 Tdiff=Tave-Tamb
650 PRINT "TPLATE-TAMB =";Tdiff
660 PRINT
670 GET AVERAGE TEMP IN INSULATION
680 Tins1=0.
690 FOR I=147 TO 149
700 OUTPUT 709;"AI";I;"VT1"
710 ENTER 709;X
720 E(I)=X*1000.
730 T(I)=26.573+E(I)-1.936879+E(I)*E(I)-.99785+E(I)*E(I)*E(I)-.251277+E(I)*E(I)
    )*E(I)*E(I)
750 Tins1=Tins1+T(I)
760 PRINT USING 480;I,E(I),T(I)
770 NEXT I
780 Tins1=Tins1/3.
790 Tins2=0.
800 FOR I=150 TO 152
810 OUTPUT 709;"AI";I;"VT1"
820 ENTER 709;X
830 E(I)=X*1000.
840 T(I)=26.573+E(I)-1.936879+E(I)*E(I)-.99785+E(I)*E(I)*E(I)-.251277+E(I)*E(I)
    )*E(I)*E(I)
850 PRINT USING 480;I,E(I),T(I)
870 Tins2=Tins2+T(I)
880 NEXT I
890 Tins2=Tins2/3.
900 PRINT
910 PRINT "TINS1 =";Tins1," TINS2 =";Tins2
920 PRINT
930 ENTER VALUES OF THERMALCONDUCT., AREA, AND THICKNESS OF INSULATION
940 K=.04      W/M DEG C
950 Dx=.0254    M
960 A=.4397     M^2
970 CALCULATE HEAT FLUX THROUGH INSULATION
980 Qins=K*A*(Tins1-Tins2)/Dx
990 GET Q IN (WATTS)
1000 Qin=Volts*Amps
1010 Qcond=Qin-Qins
1020 PRINT "Q IN =";Qin," QINSULATION =";Qins," QCONDUCTION =";Qcond
1030 PRINT "*****"
1040 STOP
1050 END

```

```

10  PROGRAM STANFEC
20  |
30  |THIS PROGRAM ACQUIRES MULTIPLE CHANEL THERMOCOUPLE DATA
40  |CREATES AND CREATES A FILE TO BE READ BY OTHER PROGRAM.
50  |UPDATED BY CRTIZ, JULY 1987.
60  |
70  |
80  MASS STORAGE IS ":INTERNAL,4,1"
90  CREATE BDAT "TDAFC026",352,8  |OPEN FILE TO RETRIEVE BASELINE TEMPERATURES
100 ASSIGN @Path_1 TO "TDAFC026"
110 CREATE BDAT "IDAF026",11,3
120 ASSIGN @Path_2 TO "IDAF026"  |OPEN FILE TO RETRIEVE INPUT DATA
130 DIM E(200),T(200)
140 PRINTER IS 1
150 |
160 PRINT "ARE YOU WORKING WITH(1), OR WITHOUT(2) FILMCOOLING?"
170 INPUT Ans
180 IF Ans=1 THEN GOTO 186J  |SUBROUTINE FOR FILMCOOLING DATA
190 |
200 |CHANNELS 0-75, 120-150
210 |COPPER CONSTANTAN THERMOCOUPLES
220 |
230 PRINT "ENTER RUN # (MONTH,DAY,YEAR,HOUR,MINUTES=MMDDYY.HHMM)"
240 INPUT Runno
250 PRINT "RUN # (MONTH,DAY,YEAR,HOUR,MINUTES) =" ;Runno
260 PRINT
270 |
280 |ENTER AMPS AND VOLTS FROM VARIAC
290 PRINT "ENTER CURRENT(AMPS.)"
300 INPUT Amps
310 PRINT "ENTER VOLTAGE(VOLTS)"
320 INPUT Volts
330 PRINT "AMPS =" ;Amps,"VOLTS =" ;Volts
340 PRINT
350 |ENTER AMBIENT CONDITIONS
360 PRINT "ENTER AMBIENT PRESSURE(IN HG)"
370 INPUT Pamb
380 PRINT "ENTER AMBIENT TEMPERATURE(DEG C)"
390 INPUT Tamb
400 PRINT "ENTER PRESSURE DIFFERENCE(IN H2O)"
410 INPUT Deltap
420 PRINT "PAMB(IN HG)=" ;Pamb,"DELTAP(IN H2O)=" ;Deltap,"TAMB(DEG C)=" ;Tamb
430 PRINT
440 |
450 DISP "(HIT<CONTINUE>)"
460 PAUSE
470 PRINTER IS 1
480 PRINT "TEMPERATURES DEG C"
490 PRINT "-----"
500 PRINT
510 PRINT "RUN # (MONTH,DAY,YEAR,HOUR,MIN) =" ;Runno
520 PRINT

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530 PRINT "No T DEG C"
540 I ACQUIRE THERMOCOUPLE READINGS
550 PRINT
560 FOR I=1 TO 79
570 OUTPUT 709;"AI";I;"VT1"
580 ENTER 709;X
590 E(I)=X*1000000
600 T(I)=-.016205+.025846*E(I)-.000000581*E(I)*E(I)
610 PRINT USING 620;I,T(I)
620 INAGE 000,4X,00.00
630 OUTPUT @Path_1;T(I)
640 NEXT I
650 I
660 FOR I=120 TO 146
670 OUTPUT 709;"AI";I;"VT1"
680 ENTER 709;X
690 E(I)=X*1000000
700 T(I)=-.01925+.025846*E(I)-.000000581*E(I)*E(I)
710 II=I-10
720 PRINT USING 620;II,T(I)
730 OUTPUT @Path_1;T(I)
740 NEXT I
750 IGET AMBIENT TEMPERATURE
760 OUTPUT 709;"AI";0;"VT1"
770 ENTER 709;X
780 E(0)=X*1000.
790 T(0)=-25.573+E(0)-1.936879*E(0)+E(0)+.997875*E(0)+E(0)*E(0)-.251277*E(0)^4
800 Tchamb=T(0)
810 PRINT "THERMOCOUPLE AMBIENT TEMP.(DEG C) ="Tchamb
820 PRINT
830 IGET THE REST OF THERMOCOUPLES
840 FOR I=147 TO 150
850 OUTPUT 709;"AI";I;"VT1"
860 ENTER 709;X
870 E(I)=X*1000.
880 T(I)=-25.573+E(I)-1.936879*E(I)+E(I)+.997875*E(I)+E(I)*E(I)-.251277*E(I)^4
890 PRINT USING 620;I,T(I)
900 OUTPUT @Path_1;T(I)
910 NEXT I
920 ASSIGN @Path_1 TO *
930 ITRANSFORM TO SI UNITS
940 I
950 Pamb=Pamb+3325.82 IPASCALS(N/M^2)
960 Deltap=Deltap+248.7 IPASCALS(N/M^2)
970 Fstemp=T(147)+273.15 IDEG KELVIN
980 Ro=Pamb/((287*Fstemp) AIR DENSITY (KG/M3)
990 Uinf=((2*Deltap/Ro)^(.5) IFREE STREAM VELOCITY (M/S)
1000 I
1010 PRINT
1020 OUTPUT @Path_2;Runno,Amps,Volts,Pamb,Deltap,Tamb,Tchamb,Uinf,Ro,Fstemp,Ans
1030 ASSIGN @Path_2 TO *
1040 I
1050 GOTO 1190
1060 ISUBROUTINE TO CALCULATE FILM COOLING DATA

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```

1070 PRINTER IS 1
1080 PRINT "ENTER FLOW % FROM ROTOMETER"
1090 INPUT Flw
1100 PRINT "ENTER PLENUM FRESSURE DIFFERENCE (IN H2O)"
1110 INPUT Delpi
1120 Delpi=Delpi*248.7
1130 Flw=Flw*.000093456
1140 CREATE BOAT "FILOT26",2,8
1150 ASSIGN @Path3 TO "FILOT26"      !OPEN FILE TO RETRIEVE FILMCOOLING DATA
1160 OUTPUT @Path3:Flw,Delpi
1170 ASSIGN @Path3 TO *
1180 GOTO 190
1190 MASS STORAGE IS ":INTERNAL,4"
1200 END

```

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10  | PROGRAM STANF02
20  |
30  | 110 M/S FREE STREAM VELOCITY, 13 INJECTION HOLES OPEN
40  | THIS PROGRAM ACQUIRES MULTIPLE CHANEL THERMOCOUPLE DATA
50  | CALCULATES HEAT TRANSFER COEFFICIENTS AND STANTON NUMBERS RATIOS
60  | AND FILM COOLING PARAMETERS.
70  | LIGRANI/ORTIZ/JOSEPH VERSION, NOVEMBER 1986
80  | UPDATED BY ORTIZ, JULY 1987.
90  |
100 |
110 | MASS STORAGE IS ":INTERNAL,4,1"
120 | CREATE BDAT "STRFCV10",504,8      | OPEN FILE TO RETRIEVE STANTON Nos RATIOS
130 | ASSIGN @Path_4 TO "STRFCV10"
140 | DIM T(200),H(200),St(200),X1(8),H1(8),St1(8),X2(200),Z(200),Stf(200),
150 | DIM Ho(200),Sto(200),X1a(8),X2a(200),Zo(200),Stfa(200),Stfb(200)
160 |
170 | PRINTER IS 1
180 |
190 | PRINT "ARE YOU USING VORTEX GENERATOR? (3,Y OR 4,N) "
200 | INPUT Y
210 | IF Y=3 THEN
220 |     PRINT "ENTER TYPE OF VORTEX GENERATOR"
230 |     INPUT Vort
240 |     PRINT "ENTER LOCATION FROM CENTER LINE IN cm"
250 |     INPUT Loc
260 | ELSE
270 |     GOTO 290
280 | END IF
290 | PRINTER IS 701
300 | PRINT CHR$(27);CHR$(36);CHR$(108);CHR$(52);CHR$(52);CHR$(70)
310 | PRINT CHR$(27);CHR$(36);CHR$(108);CHR$(49);CHR$(76)
320 |
330 | ASSIGN @Path1 TO "TDAFC10"
340 | FOR I=1 TO 130
350 |     ENTER @Path1:T(I)
360 | NEXT I
370 | ASSIGN @Path2 TO "IDAFC10"
380 | ENTER @Path2:Runno,Amps,Volts,Pamb,Deltap,Tamb,Tchamb,Uinf,Ro,Fstemp,Ans
390 | PRINT
400 |
410 | DISP "(HIT<CONTINUE>)"
420 | PAUSE
430 | IF Ans=1 THEN
440 |     PRINT "STANTON NUMBER RESULTS WITH FILM COOLING"
450 | ELSE
460 |     PRINT "STANTON NUMBER RESULTS"
470 | END IF
480 | PRINT "*****"
490 | PRINT
500 | PRINT "RUN # (MONTH,DAY,YEAR,HOUE,MIN)=";Runno
510 | PRINT
520 | IF Y=3 THEN

```

```

530 PRINT "VORTEX GENERATOR IS No =" ;Vort," LOCATED AT (cm) =" ;Loc
540 PRINT
550 ELSE
560 GOTO 580
570 END IF
580 IF Ans=1 THEN GOTO 2240
590 PRINT OUT DATA
600 PRINT "AMPS =" ;Amps," VOLTS =" ;Volts
610 PRINT
620 PRINT "AMBIENT PRESSURE (N/M^2) =" ;Pamb," DELTA P (N/M^2) =" ;Deltap
630 PRINT
640 !
650 PRINT "AIR DENSITY (KG/M3) =" ;Ro," VELOCITY (M/S) =" ;Uinf
660 PRINT
670 PRINT "FREE STREAM TEMP.(DEG K) =" ;Fstemp
680 PRINT
690 PRINT "THERMOMETER AMBIENT TEMPERATURE (DEG C) =" ;Tamb
700 PRINT
710 !CALCULATE THE AVERAGE PLATE TEMPERATURE
720 !
730 Tave=0.
740 FOR I=1 TO 128
750     Tave=Tave-T(I)
760 NEXT I
770 Tave=Tave/128
780 PRINT "AVERAGE PLATE TEMPERATURE, MEASURED (DEG C) =" ;Tave
790 PRINT
800 !ENERGY BALANCE
810 !
820 Tdiff=Tave-Tchamb
830 Qcond=.683+.854*Tdiff+.016*Tdiff^2
840 Tavabs=Tave+273.15
850 Tchabs=Tchamb+273.15
860 Qrad=.20000002189*(Tavabs^4-Tchabs^4)
870 Qin=Amps*Volts
880 Qconv=Qin-Qcond-Qrad
890 Delt=Tavabs-Fstemp
900 !
910 PRINT "T PLATE - T FSTREAM (DEG C) =" ;Delt,"POWER IN (WATTS) =" ;Qin
920 PRINT
930 PRINT "CONDUCTION LOSS (WATTS) =" ;Qcond,"CONVECTION LOSS (WATTS) =" ;Qconv
940 PRINT
950 PRINT "RADIATION LOSS (WATTS) =" ;Qrad
960 PRINT
970 !WALL TEMPERATURES CORRECTIONS
980 !
990 Cp=1025.           !SPECIFIC HEAT FOR AIR
1000 Cr=.014           !CONTACT RESISTANCE CORRECTION FACTOR
1010 Dt=Cr*Qconv        !DELTA TEMP. DUE TO CONTACT RESISTANCE
1020 Q=Qconv/.4897      !CONVECTION LOSS CORRECTION
1030 !
1040 Tcavbs=Tavabs-Dt
1050 Delto=Tcavbs-Fstemp
1060 Theta=(Tijabs-Fstemp)/Delto

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1610 Z(M)=Z(I)
1620 X2(M)=X3
1630 FOR I=M+1 TO J+2:
1640 X2(I)=X3
1650 Z(I)=Z(I-1)+1.27
1660 NEXT I
1670 X3=X3+.2
1680 NEXT J
1690 FOR I=1 TO 126
1700 OUTPUT @Path_4:Str(I),Str(I),X2(I),Z(I)
1710 PRINT USING "1720: I,X2(I),Z(I),H(I),Str(I),Str(I)
1720 IMAGE DDD,2X,DD.CC,3X,3D.DD,5X,5D.DDD2,5X,5D.DDD2,5X,D.3DE
1730 NEXT I
1740 ASSIGN @Path_4 TO * ICLOSE FILE WITH STANTON NUMBERS RATIOS
1750 I
1760 ICALCULATE LOCAL REYNOLDS NUMBER
1770 I
1780 PRINT
1790 I
1800 Nu=.0000155 ICINEMATIC VISCOSITY FOR AIR (M2/S)
1810 Fac=Uinf/Nu
1820 X1(1)=1.15
1830 X1(2)=1.25
1840 X1(3)=1.40
1850 X1(4)=1.60
1860 X1(5)=1.80
1870 X1(6)=2.00
1880 I
1890 FOR I=1 TO 6
1900 Rey(I)=X1(I)*Fac
1910 NEXT I
1920 I
1930 ICALCULATE AVERAGE STANTON NUMBER
1940 FOR I=1 TO 6
1950 H(I)=0.
1960 M=I*21-20
1970 FOR J=M TO I+21
1980 H(I)=H(I)+H(J)
1990 NEXT J
2000 H(I)=H(I)/21
2010 St(I)=H(I)/(Re*Uinf*Cp)
2020 NEXT I
2030 PRINT
2040 I
2050 ASSIGN @Path7 TO "STAV2"
2060 FOR I=1 TO 6
2070 ENTER @Path7:X1o(I),Reo(I),St1o(I)
2080 Strav(I)=St1(I)/St1o(I)
2090 NEXT I
2100 CREATE BDAT "STAVFCV",18,8
2110 ASSIGN @Path_5 TO "STAVFCV"
2120 IPRINT AVERAGE STANTON NUMBERS
2130 I
2140 PRINT "ROW# X(M) REYNOLDS No St/Sto Ave "

```

```

1070 I
1080 PRINT "TPLATE - T FREESTREAM CORRECTED (DEG C)=";Delta
1090 PRINT
1100 PRINT "AVERAGE PLATE TEMP. CORRECTED (DEG C)=";Tave-Dt
1110 PRINT
1120 PRINT "NONDIMENSIONAL TEMP. THETA =" ;Theta
1130 PRINT
1140 PRINT "No      X(M)      Z(CM)      H(W/M^2 C)      St/Sto      St/Stf"
1150 PRINT "*****"
1160 PRINT
1170 ASSIGN @Path6 TO "HDATA2"
1180 ASSIGN @Path7 TO "STAFCD8"
1190 I
1200 FOR I=1 TO 125
1210 ENTER @Path6;Ho(I),Sto(I),XZo(I),Zo(I)
1220 ENTER @Path7;Stf(I)
1230 NEXT I
1240 !CALCULATE THE HEAT TRANSFER COEFFICIENTS AND SATANTON NUMBERS
1250 I
1260     FOR I=1 TO 126
1270         T(I)=T(I)-Dt
1280         H(I)=Q/(T(I)-Tf(127))
1290         St(I)=H(I)/(Ro*Uinf* Cp)
1300         Str(I)=St(I)/Sto(I)
1310         Stf(I)=St(I)/Stf(I)
1320     NEXT I
1330 !GENERATE X AND Z POSITION FOR EACH INDIVIDUAL THERMOCOUPLE
1340 Z(1)=-12.7      I (CM)
1350 X2(1)=1.15
1360 FOR I=2 TO 21
1370 X2(I)=1.15
1380 Z(I)=Z(I-1)+1.27
1390 NEXT I
1400 Z(22)=Z(1)
1410 X2(22)=1.25
1420 FOR I=23 TO 42
1430 X2(I)=1.25
1440 Z(I)=Z(I-1)+1.27
1450 NEXT I
1460 Z(43)=Z(1)
1470 X2(43)=1.40
1480 FOR I=44 TO 63
1490 X2(I)=1.40
1500 Z(I)=Z(I-1)+1.27
1510 NEXT I
1520 Z(64)=Z(1)
1530 X2(64)=1.6
1540 FOR I=65 TO 84
1550 X2(I)=1.6
1560 Z(I)=Z(I-1)+1.27
1570 NEXT I
1580 X3=1.8
1590 FOR J=5 TO 6
1600 M=J*21-22

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```

2150 PRINT "*****"
2160 FOR I=1 TO 6
2170 PRINT USING 2180:I,X1(I),Rey(I),Strav(I)
2180 IMAGE DD,4X,DD.00,4X,D.4DE,7X,D.4DE
2190 OUTPUT @Path_5:X1(I),Rey(I),Strav(I)
2200 NEXT I
2210 ASSIGN @Path_5 TO *
2220 I
2230 GOTO 2580
2240 !SUBROUTINE TO CALCULATE DISCHARGE COEFFICIENTS
2250 I
2260 ASSIGN @Path3 TO "FILD10"
2270 ENTER @Path3:Flw,Delp1
2280 !GET AVERAGE PLENUM TEMPERATURE
2290 Tpl=0
2300 FOR I=106 TO 130
2310 Tpl=Tpl+T(I)
2320 NEXT I
2330 Tpl=Tpl/3
2340 !CONVERT PLENUM TEMP. TO INJECTION TEMP.
2350 Tinj=1.45463+Tpl*.868182
2360 Tijabs=Tinj-273.15
2370 Uinj=Flw/.000501458 !FOR 13 INJ. HOLES
2380 !Uinj=Flw/.000436 !FOR 7 INJ. HOLES
2390 Ton=Tijabs-(Uinj**2/(2*1005))
2400 Roc=Pamb/(Ton*287)
2410 Imflx=Roc*Uinj !INJECTION MASS FLUX
2420 Rop1=Pamb/(Tijabs*287) !TOTAL DENSITY BASED ON To
2430 U3=(Delp1+2/Rop1)**.5
2440 Pmflx=Rop1*U3
2450 Cd=Imflx/Pmflx
2460 Red=Uinj*.009525/.0000156
2470 M=Imflx/(Roc*Uinf) !BLOWING RATIO
2480 Vrat=Uinj/Uinf !VELOCITY RATIO
2490 Mfr=Roc*Uinj**2/(Roc*Uinf**2) !MOMENTUM FLUX RATIO
2500 I
2510 !PRINT RESULTS
2520 PRINT "INJECTION TEMPERATURE (C)=";Tinj,"PLENUM TEMP (C)=";Tpl
2530 PRINT
2540 I
2550 PRINT "PLENUM PRESSURE DIFF. (N/M^2)=";Delp1
2560 PRINT
2570 PRINT "COOLANT DENSITY KG/M^3 =" ;Roc," DENSITY RATIO =" ;Roc/Ro
2580 PRINT
2590 PRINT "INJECTION VELOCITY (M/S)=";Uinj,"MASS FLUX (KG/M^2 S)=";Imflx
2600 PRINT
2610 PRINT "REYNOLDS No (DIA)=";Red,"DISCHARGE COEFF. Cd =" ;Cd
2620 PRINT
2630 PRINT "BLOWING RATIO =" ;M," VELOCITY RATIO =" ;Vrat
2640 PRINT
2650 PRINT "MOMENTUM FLUX RATIO =" ;Mfr
2660 PRINT
2670 GOTO 590
2680 MASS STORAGE IS ":INTERNAL,4"
2690 END

```

```

10  REM PROGRAM ACOTPRO
20  REM THIS PROGRAM ACQUIRES TEMPERATURES FROM A THERMOCCOUPLE
30  REM MONTED ON A AUTOMATIC TRAVERSE MECHANISIM AND FROM A FREE
40  REM STREAM VELOCITY THERMCOUPLE TO PLOT THE TEMPERATURES PROFILES
50  REM USING PROGRAM PLOTDE
60  REM
70  REM BY ALFREDO ORTIZ, AUGUST,1987
80  REM
90  REM VARIABLE NAMES
100 REM
110 REM E(I) IS THE VOLTAGE READ FROM THE DATA ACQUISTION SYSTEM
120 REM T(I) IS THE CONVERSION FROM VOLTAGE TO TEMPERATURES
130 REM
140 REM PAMB=AMBIENT PRESSURE
150 REM TFS=FREE STREAM TEMP(KELVIN)
160 REM RO=DENSITY (KG/M3)
170 REM UINF=VELOCITY OF THE FREESTREAM
180 REM
190 DIM Y(1000),Z(1000),T(1000),TI(1000),D(1000)
200 REM
210 REM
220 INPUT "ENTER DATE,(MMDDYY)",N8
230 INPUT "ENTER TIME,(HHMM)",N9
240 REM
250 INPUT "ENTER DISTANCE FROM THE B.L. TRIP., X(M)",X1
260 INPUT "ENTER POINTS SPANWISE",M3
270 INPUT "ENTER POINTS VERTICAL (MUST BE AN INTEGER)",N3
280 REM N3 MUST BE AN EVEN INTEGER
290 INPUT "ENTER SPANWISE RESOLUTION(IN)",Z4
300 INPUT "ENTER VERTICAL RESOLUTION(IN)",Y4
310 INPUT "INITIAL Z(IN)",Z3
320 INPUT "INITIAL Y(IN)",Y3
330 REM
340 Z(1)=Z3
350 Y(1)=Y3
360 N7=N3/2
370 FOR I7=1 TO N7
380   I6=I7-1
390   J1=2*I6+M3+2
400   J2=2*I6+M3+M3
410   FOR K=J1 TO J2
420     Z(K)=Z(K-1)+Z4
430     Y(K)=Y(K-1)
440   NEXT K
450   J3=2*I6+M3+M3+1
460   Z(J3)=Z(J3-1)
470   Y(J3)=Y(J3-1)+Y4
480   J4=J3+1
490   J5=2*I6+M3+2*M3
500   FOR K=J4 TO J5
510     Z(K)=Z(K-1)-Z4
520     Y(K)=Y(K-1)
530   NEXT K

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540 IF I7=N7 THEN S90
550 J6=J5+1
560 Z(J6)=Z(J6-1)
570 Y(J6)=Y(J6-1)+Y4
580 NEXT I7
590 REM
600 1 ENTER FREE STREAM TEMPERATURE FROM DAS.
610 OUTPUT 709:"AI";151;"VT1"
620 ENTER 709:X
630 E=X*1000000
640 Tfs=-.0793171+.026105454+E-.000000578+E+E
650 Tfs=Tfs+273.15
660 REM ENTER AMBIENT CONDITIONS
670 INPUT "ENTER PAMB (IN.OF HG)";Pamb
680 INPUT "ENTER PRESSURE DIFFERENCE (IN OF H2O)";Deltap
690 REM
700 REM CONVERSION TO SI UNITS
710 Pamb=Pamb*3385.82
720 Ro=Pamb/(267*Tfs)
730 Deltap=Deltap*248.7
740 REM FREESTREAM VELOCITY
750 Uinf=(2*Deltap/Ro)**.5
760 REM
770 REM ENTER THE LOOP FOR ACQUIRING EACH TEMPERATURE COMPUTING COEFFICIENTS
780 REM AND COMPUTING TWO TEMPERATURE COEFFICIENTS AND TWO TEMPERATURES
790 PRINTER IS 701
800 PRINT CHR$(27);CHR$(38);CHR$(108);CHR$(53);CHR$(52);CHR$(70)
810 PRINT CHR$(27);CHR$(36);CHR$(108);CHR$(49);CHR$(76)
820 !
830 PRINT "TEMPERATURE PROFILE COMPUTATION "
840 PRINT "=====
850 PRINT
860 PRINT "DATE OF RUN IS";N8," TIME =";N9
870 PRINT
880 PRINT "DISTANCE FROM THE BOUNDARY LAYER TRIP, X (M)=";X1
890 PRINT
900 PRINT "DENSITY(KG/M^3)";Ro
910 PRINT
920 PRINT "FREESTREAM VELOCITY (M/S)";Uinf
930 PRINT
940 PRINT "PAMBIENT(N/M^2)";Pamb
950 PRINT
960 PRINT "FREE STREAM TEMPERATURE (DEG C) =";Tfs-273.15
970 PRINT
980 PRINT "POINTS SPANWISE";M3
990 PRINT
1000 PRINT "POINTS VERTICAL";N3
1010 PRINT
1020 PRINT "SPANWISE RESOLUTION (IN)";Z4
1030 PRINT
1040 PRINT "VERTICAL RESOLUTION (IN)";Y4
1050 PRINT
1060 PRINT "INITIAL Z(IN)";Z3
1070 PRINT

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1090 PRINT "INITIAL Y(IN)",Y3
1090 PRINT
1100 PRINT "*****"
1110 PRINT
1120 PRINT "      Y      Z      T      TFS      DT"
1130 PRINT "===== "
1140 PRINT
1150 DISP "HIT <<CONTINUE FOR DAS>>"
1160 PAUSE
1170 K9=0
1180 K2=M3+N3
1190 FOR K=1 TO K2
1200 K9=K
1210 REM
1220 WAIT 10
1230 REM ACQUIRE THE TEMPERATURE FOR EACH POSITION
1240 G1=0
1250 REM
1260 FOR J=1 TO 25 !ENTER THE DAS AND SAMPLE OF TEMPERATURE 25 TIMES
1270 OUTPUT 709;"AI";152;"VT1"
1280 ENTER 709;X
1290 G1=G1+X
1300 NEXT J
1310 REM
1320 X=G1/25 !AVERAGE THE VALUES
1330 E=X*1000000
1340 T(K)=.1626703+.02566713*E-.000000486*E*E !CONVERSION FROM VOLTAGE TO TEM
PERATURE
1350 REM
1360 ! GET FREE STREAM TEMP 5 TIMES AND AVERAGE IT
1370 G4=0
1380 FOR I=1 TO 5
1390 OUTPUT 709;"AI";151;"VT1"
1400 ENTER 709;X
1410 G4=G4+X
1420 NEXT I
1430 X=G4/5
1440 E=X*1000000
1450 T1(K)=-.0763171+.026105454*E-.0000000678*E*E
1460 D(K)=T(K)-T1(K)
1470 PRINT USING 1480;Y(K),Z(K),T(K),T1(K),D(K)
1480 IMAGE MOD.00,2X,MOD.00,2X,MOD.00,3X,MOD.00,3X,50.00E
1490 REM
1500 NEXT K
1510 REM
1520 MASS STORAGE IS ":INTERNAL,4,1"
1530 CREATE BOAT "TPR014",2400,3
1540 ASSIGN @Path2 TO "TPR014"
1550 FOR I=1 TO K9
1560 OUTPUT @Path2;Y(I),Z(I),D(I)
1570 NEXT I
1580 ASSIGN @Path2 TO +
1590 MASS STORAGE IS ":INTERNAL,4"
1600 END

```

```

10  IPROGRAM PLOTPRUN
20  I THIS PROGRAM READS THE FILE TPRO AND PLOT TEMPERATURES
30  I PROFILES
40  DIM Y1(800),Z0(800),X$(800)(11),V1(800),Z1(40),Z2(40),CS(13)(1)
50  I V1(I)=0(I) :TEMPERATURE DIFFERENCE.
60  I
70  INPUT "ENTER RUN NUMBER ",Runno
80  FS="DATE="
90  MASS STORAGE IS ":INTERNAL,4,1"
100  ASSIGN @Path1 TO "TPRO7"
110  FOR I=1 TO 800
120  ENTER @Path1:Y1(I),Z0(I),V1(I)
130  Y1(I)=Y1(I)*2.54
140  Z0(I)=Z0(I)*2.54
150  NEXT I
160  FOR I=1 TO 800
170  IF V1(I)<1.2 THEN X$(I)="0"
180  IF V1(I)<1.5 AND V1(I)>1.2 THEN X$(I)="1"
190  IF V1(I)<1.8 AND V1(I)>1.5 THEN X$(I)="2"
200  IF V1(I)<2.1 AND V1(I)>1.8 THEN X$(I)="3"
210  IF V1(I)<2.4 AND V1(I)>2.1 THEN X$(I)="4"
220  IF V1(I)<2.7 AND V1(I)>2.4 THEN X$(I)="5"
230  IF V1(I)<3.0 AND V1(I)>2.7 THEN X$(I)="6"
240  IF V1(I)<3.3 AND V1(I)>3.0 THEN X$(I)="7"
250  IF V1(I)<3.6 AND V1(I)>3.3 THEN X$(I)="8"
260  IF V1(I)<3.9 AND V1(I)>3.6 THEN X$(I)="9"
270  IF V1(I)<4.2 AND V1(I)>3.9 THEN X$(I)="a"
280  IF V1(I)<4.5 AND V1(I)>4.2 THEN X$(I)="b"
290  IF V1(I)>4.5 THEN X$(I)="c"
300  NEXT I
310  BINIT
320  PLOTTER IS 705,"HPGL"
330  I PLOTTER IS CRT,"INTERNAL"
340  GRAPHICS ON
350  CSIZE 2.5,.65
360  MOVE 35,14
370  LABEL "EMBEDDED VORTEX 10 M/S WITH FILM COOLING, M=0.98"
380  MOVE 35,11
390  LABEL "X=1.480 M, UNHEATED PLATE,VORTEX GEN. AT 4.75 cm"
400  MOVE 75,63
410  LABEL USING "SA,*,60.40";FS,Runno
420  CSIZE 4.5,.65
430  MOVE 40,65
440  LABEL "TEMPERATURE PROFILES"
450  CSIZE 3.5,.65
460  MOVE 67,17
470  LABEL "Z (CM) "
480  DEG
490  LDIR 90
500  MOVE 21,45
510  LABEL "Y (CM) "
520  LDIR 0

```

```

530 VIEWPORT 30,116,25,83
540 WINDOW -16,6,0,12
550 FRAME
560 AXES .5,.5,0,0,2,2
570 AXES .5,.5,-16,12,2,2
580 AXES .5,.5,6,12,2,2
590 CSIZE 2.0,.65
600 MOVE -15.2,11.10
610 LABEL "TEMP. DIFF. RANGES"
620 A=10.65
630 FOR K=0 TO 12
640 B=A-K+.35
650 MOVE -14.3,B
660 IF K<2 THEN
670 Z2(0)=-.2
680 Z1(0)=.2
690 Z2(1)=.2
700 Z1(1)=.5
710 ELSE
720 Z2(K)=Z1(K-1)
730 Z1(K)=Z2(K)+.5
740 END IF
750 IF K=9 THEN GOTO 780
760 LABEL USING "0,2X,00.0,X,00.0";K,Z2(K),Z1(K)
770 GOTO 820
780 C$(10)="a"
790 C$(11)="b"
800 C$(12)="c"
810 LABEL USING "A,2X,00.0,X,00.0";C$(K),Z2(K),Z1(K)
820 NEXT K
830 CSIZE 1.3,.72
840 FOR I=1 TO 800
850 MOVE Z0(I),Y1(I)
860 IF Y1(I)>6.0 AND Z0(I)<-10. THEN GOTO 920
870 LABEL USING "A";X$(I)
880 NEXT I
890 CLIP OFF
900 CSIZE 2.0,.65
910 FOR I=-.2 TO 11.8 STEP 2
920 MOVE -17.5,I
930 II=I+.2
940 LABEL USING "#,00.0";II
950 NEXT I
960 FOR J=-17.0 TO 5.0 STEP 2
970 MOVE J,-.7
980 JI=J+1.0
990 LABEL USING "#,00.0";JI
1000 NEXT J
1010 MASS STORAGE IS ":INTERNAL,4"
1020 END

```

```

10  IPROGRAM PTSTAV
20  ITHIS PROGRAM READS A DATA FILE AND PLOTS AVERAGE STANTON NUMBERS
30  IVERSUS REYNOLDS NUMBERS.
40  I
50  DIM Rey(6),X1(6),St1(6),CS(6),St(6)
60  MASS STORAGE IS ":INTERNAL,4,1"
70  ASSIGN @Path2 TO "STAV1"
80  FOR I=1 TO 6
90  ENTER @Path2;X1(I),Rey(I),St1(I)
100 NEXT I
110 PRINTER IS 1
120 PRINT "ENTER RUN NUMBER TO WHICH THIS DATA CORRESPOND (MMDDYY.HHMM)"
130 INPUT Runno
140 F#="DATE ="
150 GINIT
160 PLOTTER IS 705,"HPGL"
170 IFLOTTER IS CRT,"INTERNAL"
180 GRAPHICS ON
190 CSIZE 2.5,.65
200 MOVE 42,14
210 LABEL "FREESTREAM IS M/S, NO FILM COOLING"
220 CSIZE 4.5,.65
230 MOVE 40,85
240 LABEL "AVERAGED STANTON NUMBERS"
250 CSIZE 2.5,.65
260 MOVE 75,63
270 LABEL USING "SA,#,60.40";F#,Runno
280 CSIZE 3.4,.65
290 MOVE 62,17
300 LABEL "REx * 10^-6"
310 DEG
320 LDIR 90
330 MOVE 22,33
340 LABEL "STANTON No *10^-3"
350 LDIR 0
360 VIEWPORT 30,115,25,83
370 WINDOW 0,5,0,6
380 FRAME
390 AXES .5,.5,0,0,2,1
400 AXES .5,.5,5.6,2,1
410 CLIP OFF
420 CSIZE 2.0,.65
430 LORG 2
440 FOR I=0 TO 6 STEP .5
450     MOVE -.32,I
460     LABEL USING "#,0.00";I
470 NEXT I
480 LORG 4
490 FOR J=0. TO 5.0 STEP .5
500     MOVE J,-.22
510     LABEL USING "#,00.0";J
520 NEXT J

```

```

530  ENTER VALUES FOR ANALYTICAL FORMULA
540  Z1=1.1          1 METERS
550  Pr=.71          1 PRANDTL No FOR AIR
560  FOR I=1 TO 8
570  St(I)=((.030*(Rey(I))^(-.2))*(<math>1-(Z1/X1(I))^{.9}</math>)^(-.111))/Pr^1.4
580  St(I)=St(I)*1.0E+3
590  Rey(I)=Rey(I)+1.0E-6
600  PLOT Rey(I),St(I)
610  NEXT I
620  CSIZE 1.3,.72
630  FOR I=1 TO 8
640  C$(I)="X"
650  St1(I)=St(I)*1.0E+3
660  MOVE Rey(I),St1(I)
670  LABEL USING "A"1C$(I)
680  PENUP
690  NEXT I
700  MASS STORAGE IS ":INTERNAL,4"
710  END

```

```

10  PROGRAM PTSTLC
20  !THIS PROGRAM READS A DATA FILE AND PLOTS SPANWISE VARIATIONS
30  !OF HEAT TRANSFER COEFFICIENTS
40  !
50  DIM H(200),St(200),Rey(5),Z(200),X1(6),X2(200),B(126),Cs(5)(8)
60  MASS STORAGE IS ":INTERNAL,4,1"
70  ASSIGN @Path1 TO "HDATA2"
80  FOR I=1 TO 125
90  ENTER @Path1;H(I),St(I),X2(I),Z(I)
100 NEXT I
110 F$="DATE ="
120 INPUT "ENTER RUN NUMBER (MMDDYY.HHMM)",Runno
130 GINIT
140 PLOTTER IS 705,"HPGL"
150 !PLOTTER IS CRT,"INTERNAL"
160 GRAPHICS ON
170 CSIZE 2.5,.65
180 MOVE 42,14
190 LABEL "FREE STREAM 10 M/S, NO FILM COOLING"
200 CSIZE 4.5,.65
210 MOVE 20,85
220 LABEL "SPANWISE HEAT TRANSFER COEFFICIENT"
230 CSIZE 2.5,.65
240 MOVE 75,83
250 LABEL USING "6A,#,60.40";F$,Runno
260 CSIZE 3.5,.65
270 MOVE 55,17
280 LABEL "Z (CM) "
290 MOVE 22,35
300 DEG
310 LDIR 90
320 LABEL "H W/M^2 DEG C"
330 LDIR 0
340 VIEWPORT 30,115,25,83
350 WINDOW -15.24,15.24,0,100
360 FRAME
370 AXES 1.27,10,-15.24,0,2,2
380 AXES 1.27,10,15.24,100,2,2
390 CSIZE 2.0,.65
400 MOVE -13,23
410 LABEL "X (M)"
420 A=22
430 FOR K=1 TO 6
440 B=A-K*3
450 Cs(1)="X=1.15"
460 Cs(2)="X=1.25"
470 Cs(3)="X=1.40"
480 Cs(4)="X=1.60"
490 Cs(5)="X=1.80"
500 Cs(6)="X=2.00"
510 MOVE -14,0
520 LABEL USING "D,8A";K,Cs(K)(1;8)
530 PENUP
540 NEXT K

```

```

550 CSIZE 1.3,.72
560 FOR J=1 TO 6
570 M=J*21-20
580 FOR I=M TO J*21
590 B(I)=J
600 MOVE Z(I),H(I)
610 LABEL USING "D";B(I)
620 PENUP
630 NEXT I
640 NEXT J
650 CLIP OFF
660 CSIZE 2.0,.65
670 LORG 2
680 FOR I=0 TO 100 STEP 10
690 MOVE -17.75,I
700 LABEL USING "#,000.D";I
710 NEXT I
720 LORG 6
730 FOR J=-15.24 TO 15.74 STEP 5.08
740 MOVE J,-2.0
750 LABEL USING "#,000.DD";J
760 NEXT J
770 MASS STORAGE IS ":INTERNAL,4"
780 END

```

```

10  IPROGRAM FLSTRTIO
20  ITHIS PROGRAM READS A DATA FILE AND PLOTS THE RATIO OF STANTON NUMBERS
30  IOVER BASE LINE STANTON NUMBERS VERSUS REYNOLDS NUMBERS.
40  I
50  DIM Rey(5),X1(6),St1(6),St2(6),Re1(6),Cs(6)(1),P#(6)(1),G#(6)(1)
60  DIM St3(6),Re3(6),St4(6),Re4(6),Str1(6),Str2(6),Str3(6)
70  ASSIGN @Path1 TO "STAV"
80  FOR I=1 TO 5
90  ENTER @Path1:X1(I),Rey(I),St1(I)
100 NEXT I
110 ASSIGN @Path2 TO "STAVFC"
120 FOR I=1 TO 5
130 ENTER @Path2:Re1(I),St2(I)
140 Str1(I)=St2(I)/St1(I)
150 NEXT I
160 ASSIGN @Path3 TO "STAVF1"
170 FOR I=1 TO 5
180 ENTER @Path3:Re3(I),St3(I)
190 Str2(I)=St3(I)/St1(I)
200 NEXT I
210 ASSIGN @Path4 TO "STAVF2"
220 FOR I=1 TO 5
230 ENTER @Path4:Re4(I),St4(I)
240 Str3(I)=St4(I)/St1(I)
250 NEXT I
260 PRINTER IS 1
270 PRINT "ENTER TODAY'S DATE (MMDDYY.HHMM):"
280 INPUT Runno
290 F#="DATE ="
300 PRINT "ENTER IN ORDER CORRESPONDING BLOWING RATIOS, M1,M2, AND M3"
310 FOR I=1 TO 3
320 INPUT M(I)
330 IECHO PRINT M
340 PRINT "M=";M(I)
350 GINIT
360 I PLOTTER IS 705,"HPGL"
370 PLOTTER IS CRT,"INTERNAL"
380 GRAPHICS ON
390 X_gdu_max=100*MAX(1,RATIO)
400 Y_gdu_max=100*MAX(1,1/RATIO)
410 CSIZE 4.5,.65
420 LORG 5
430 MOVE X_gdu_max/2,.9*Y_gdu_max
440 LABEL "FILM COOLING"
450 DEG
460 LGIR 90
470 CSIZE 3.5
480 MOVE .1*X_gdu_max,Y_gdu_max/2
490 LABEL "St/Sto"
500 LGIR 0
510 LORG 4
520 MOVE X_gdu_max/2,.20*Y_gdu_max
530 LABEL "REYNOLDS No*10^6"

```



```

540 CSIZE 2.5
550 LORG 6
560 MOVE .8*X_gdu_max,.65*Y_gdu_max
570 LABEL USING "5A, #,50.40";F$,Runno
580 VIEWPORT .2*X_gdu_max,.9*X_gdu_max,.30*Y_gdu_max,.30*Y_gdu_max
590 FRAME
600 WINDOW .6,1.6,.5,1.0
610 AXES .1,.1,.6,.3,1,1
620 AXES .1,.1,1.6,1.0,1,1
630 CSIZE 2.5
640 MOVE 1.2,.5
650 LABEL "BLOWING RATIOS"
660 A=.55
670 FOR K=1 TO 3
680 O=A-K+.2
690 B$(1)="*+M="
700 B$(2)="o=M="
710 B$(3)="+<M="
720 MOVE 1.29,O
730 LABEL USING "4A, #,0.00";B$(1),M(I)
740 NEXT K
750 CLIP OFF
760 CSIZE 2.0,.65
770 LORG 2
780 FOR I=.3 TO 1.0 STEP .1
790 MOVE .54,I
800 LABEL USING "#,0.0";I
810 NEXT I
820 LORG 6
830 FOR J=.6 TO 1.7 STEP .1
840 MOVE J,.27
850 LABEL USING "#,0.0";J
860 NEXT J
870 CSIZE 1.3,.72
880 FOR I=1 TO 6
890 C$(I)="*"
900 MOVE Rey(I),Str1(I)
910 LABEL USING "A";C$(I)
920 G$(I)="o"
930 MOVE Rey(I),Str2(I)
940 LABEL USING "A";G$(I)
950 P$(I)="+"
960 MOVE Rey(I),Str3(I)
970 PENUP
980 NEXT I
990 END

```

```

10  PROGRAM PLSTRVOR
20  !THIS PROGRAM READS A DATA FILE AND PLOTS SPANWISE VARIATIONS
30  !OF STANTON NUMBERS RATIOS BY ROWS
40  !
50  DIM Str(200),Rey(6),Z(200),X1(6),X2(200),Cs(6)(81,B(125)
60  MASS STORAGE IS ":INTERNAL,4,1"
70  ASSIGN @Path1 TO "STRDT2"
80  FOR I=1 TO 126
90  ENTER @Path1(Str(I),X2(I),Z(I)
100 NEXT I
110 F$="DATE ="
120 PRINTER IS 1
130 PRINT "ENTER RUN NUMBER TO WHICH THIS PLOT CORRESPOND (MMDDYY.NHMM)"
140 INPUT Runno
150 GINIT
160 PLOTTER IS 705,"HPGL"
170 !PLOTTER IS CRT,"INTERNAL"
180 GRAPHICS ON
190 CSIZE 2.5,.65
200 MOVE 42,14
210 LABEL "FREE STREAM 10 M/S, NO FILM COOLING "
220 CSIZE 4.5,.65
230 MOVE 20,85
240 LABEL "STANTON NUMBER RATIOS, VORTEX GEN #2"
250 CSIZE 2.5,.65
260 MOVE 70,83
270 LABEL USING "SA,*,60.40" (F$,Runno
280 CSIZE 3.5,.65
290 MOVE 65,17
300 LABEL "Z (CM) "
310 MOVE 22,45
320 DEG
330 LDIR 90
340 LABEL "St/Sto"
350 LDIR 0
360 VIEWPORT 30,116,25,83
370 WINDOW 20,-20,.4,1.4
380 FRAME
390 AXES S,.1,20,.40,1,1
400 AXES S,.1,-20,1.4,1,1
410 CSIZE 2.0,.65
420 MOVE 13.5,.85
430 LABEL "X (M)"
440 A=.80
450 FOR K=1 TO 6
460 D=A-K*.04
470 Cs(1)="X=1.15"
480 Cs(2)="X=1.25"
490 Cs(3)="X=1.40"
500 Cs(4)="X=1.60"
510 Cs(5)="X=1.80"
520 Cs(6)="X=2.00"
530 MOVE 14,D

```

```

540 LABEL USING "D,3A";K,C3(K)
550 PENUP
560 NEXT K
570 CSIZE 1.3,.72
580 FOR J=1 TO 6
590 M=J*21-20
600 FOR I=M TO J*21
610 B(I)=J
620 MOVE Z(I),Str(I)
630 LABEL USING "D";B(I)
640 PENUP
650 NEXT I
660 NEXT J
670 CLIP OFF
680 CSIZE 2.0,.55
690 LONG 2
700 FOR I=.4 TO 1.4 STEP .1
710 MOVE 21.7,I
720 LABEL USING "#,D.D";I
730 NEXT I
740 LONG 6
750 FOR J=-20 TO 20 STEP 5
760 MOVE J,.37
770 LABEL USING "#,DDD.DD";J
780 NEXT J
790 MASS STORAGE IS ":INTERNAL,4"
800 END

```

```

10  !PROGRAM PLSTROUV6
20  !THIS PROGRAM READS A DATA FILE AND PLOTS SPANWISE VARIATIONS
30  !OF STANTON NUMBERS RATIOS BY ROWS FOR FILM COOLING DATA AND
40  !FOR VORTEX DATA
50  !
60  DIM Str1(126),Str2(126),Z(126),X2(126),X3(126),Cs(126)(11),Ss(126)(11)
70  DIM Stf(126),Zf(126)
90  !
90  MASS STORAGE IS ":INTERNAL,4,1"
100  ASSIGN @Path1 TO "STRFC3"
110  ASSIGN @Path2 TO "STRFCV11"
120  !
130  FOR I=1 TO 126
140  ENTER @Path1:Stf(I),X2(I),Z(I)
150  ENTER @Path2:Str2(I),Stf(I),X3(I),Zf(I)
160  NEXT I
170  F$="DATE ="
180  PRINTER IS 1
190  PRINT "ENTER RUN NUMBER TO WHICH THIS PLOT CORRESPOND (XXXXXX.HHMM)"
200  INPUT Runno
210  GINIT
220  PLOTTER IS 705,"HPGL"
230  !PLOTTER IS CRT,"INTERNAL"
240  GRAPHICS ON
250  CSIZE 2.5,.65
260  MOVE 20,14
270  LABEL "FREE STREAM IS M/S, WITH FILM COOLING, VORTEX GEN. AT 4.75 cm"
280  CSIZE 4.5,.65
290  MOVE 40,65
300  LABEL "STANTON NUMBER RATIOS"
310  CSIZE 2.5,.65
320  MOVE 75,83
330  LABEL USING "SA,#,60.40":F$,Runno
340  CSIZE 3.5,.65
350  MOVE 65,17
360  LABEL "Z (CM)"
370  MOVE 25,45
380  DEG
390  LDIR 90
400  LABEL "St/Stc"
410  LDIR 0
420  VIEWPORT 30,116,25,63
430  WINDOW -20,20,.3,1.2
440  FRAME
450  AXES S,.1,-20,.30,1,1
460  AXES S,.1,20,1.2,1,1
470  CSIZE 3.0,.65
480  MOVE -17.5,1.2
490  LABEL "X = 2.20 M"
500  CSIZE 2.5,.65
510  MOVE 0,.4
520  LABEL "m=0.47"
530  MOVE -17.5,.41

```

AD-A195 155

THE THERMAL BEHAVIOR OF FILM COOLED TURBULENT BOUNDARY  
LAYERS AS AFFECTED BY LONGITUDINAL VORTICES(U) NAVAL  
POSTGRADUATE SCHOOL MONTEREY CA A ORTIZ SEP 87

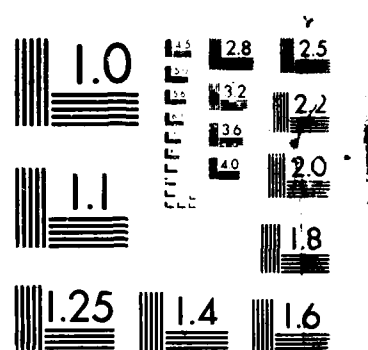
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MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

```

540 LABEL "o = WITHOUT VORTEX"
550 MOVE -17.5,.37
560 LABEL "+ = WITH VORTEX"
570 CSIZE 1.3,.72
580 FOR I=106 TO 128
590 BS(I)="o"
600 CS(I)="+ "
610 MOVE Z(I),Str1(I)
620 LABEL USING "A":BS(I)
630 MOVE Z(I),Str2(I)
640 LABEL USING "A":CS(I)
650 PENUP
660 NEXT I
670 CLIP OFF
680 CSIZE 2.0,.65
690 LOFS 2
700 FOR I=.3 TO 1.3 STEP .1
710 MOVE -21.8,I
720 LABEL USING "#,0.0":I
730 NEXT I
740 LORG 6
750 FOR J=-20 TO 20 STEP 5
760 MOVE J,.27
770 LABEL USING "#,000.00":J
780 NEXT J
790 MASS STORAGE IS ":INTERNAL,4"
800 END

```

```

10  IPROGRAM SURFCONT1
20  ITHIS PROGRAM READS A DATA FILE AND PLOTS SURFACE CONTOURS OF
30  IOF STANTON NUMBERS RATIOS ALONG THE PLATE SPAN.
40  I
50  IORTIZ VERSION JULY/87
60  DIM Str(126),Strf(126),Z(126),X2(126),B(126),Z1(5),Z2(5)
70  MASS STORAGE IS ":INTERNAL,4,1"
80  ASSIGN @Path1 TO "STRFCV12"
90  PRINTER IS 701
100 FOR I=1 TO 126
110 ENTER @Path1:Str(I),Strf(I),X2(I),Z(I)
120 NEXT I
130 F3="DATE ="
140 PRINTER IS 1
150 PRINT "ENTER RUN NUMBER TO WHICH THIS PLOT CORRESPOND (MMDDYY.HHMM)"
160 INPUT Runno
170 I
180 Stmin=.80
190 Llim=.85
200 FOR I=1 TO 126
210 IF Strf(I)<Llim THEN B(I)=0
220 IF Strf(I)=1.00 AND Strf(I)<Llim THEN B(I)=1
230 IF Strf(I)=1.10 AND Strf(I)<1.00 THEN B(I)=2
240 IF Strf(I)=1.20 AND Strf(I)>1.10 THEN B(I)=3
250 IF Strf(I)>1.20 THEN B(I)=4
260 NEXT I
270 I
280 GINIT
290 PLOTTER IS 705,"HPGL"
300 I PLOTTER IS CRT,"INTERNAL"
310 GRAPHICS ON
320 CSIZE 2.5,.65
330 MOVE 14,13
340 LABEL "FREE STREAM 10 M/S, WITH FILM COOLING, VORTEX GEN. AT 4.79 cm "
350 CSIZE 2.5,.65
360 MOVE 40,82
370 LABEL "SURFACE CONTOURS"
380 CSIZE 2.5,.65
390 MOVE 70,80
400 LABEL USING "BA,*,60.40":F3,Runno
410 CSIZE 3.5,.65
420 MOVE 50,32
430 LABEL "X (M) "
440 MOVE 15,55
450 DEG
460 LDIR 90
470 LABEL "Z (CM)"
480 LDIR 0
490 CSIZE 2.5,.65
500 MOVE 54,27
510 LABEL "St/Stf RANGES"

```



```

690  A=24
700  FOR K=0 TO 2
710  G=A-K*2.5
720  MOVE 34,G
730  Z2(0)=Stmin+K*Inc
740  Z1(0)=Stmin+(k+1)*Inc
750  Z2(1)=.98
760  Z1(1)=1.02
770  Z2(2)=1.02
780  Z1(2)=1.10
790  LABEL USING 800:K,Z2(K),Z1(K)
800  IMAGE D,2x D.30,2x D.30
810  NEXT K
820  FOR K=3 TO 4
830  G=A-(K-3)*2.5
840  MOVE 64,G
850  Z2(3)=1.10
860  Z1(3)=1.20
870  Z2(4)=1.20
880  Z1(4)=1.30
890  LABEL USING 800:K,Z2(K),Z1(K)
900  NEXT K
910  VIEWPORT 15,114,40,76
920  WINDOW 1.10,2.20,20.,-20.
930  FRAME
940  AXES .05,5.,1.10,22.,4,1
950  AXES .05,5.,2.20,-20.,4,1
960  MOVE 1.30,17
970  LABEL "M"=0.66"
980  CSIZE 1.3,.72
990  FOR I=1 TO 126
1000 MOVE X2(I),Z2(I)
1010 LABEL USING "D":B(I)
1020 PENUP
1030 NEXT I
1040 CLIP OFF
1050 CSIZE 2.0,.65
1060 LORG 2
1070 FOR I=-20 TO 20 STEP 5
1080   MOVE 1.01,I
1090   LABEL USING "*,DDD.D":I
1100 NEXT I
1110 LORG 5
1120 FOR J=1.10 TO 2.30 STEP .1
1130   MOVE J,22
1140   LABEL USING "*,D.DD":J
1150 NEXT J
1160 MASS STORAGE IS ":INTERNAL,4"
1170 ENC

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10  IPROGRAM FLSTRFC
20  !THIS PROGRAM READS A DATA FILE AND PLOTS SPANWISE VARIATIONS
30  !OF STANTON NUMBERS RATIOS BY ROWS FOR FILM COOLING DATA
40  !
50  DIM Str(200),Rey(6),Z(200),X1(6),X2(200),Cs(6)(8),B(126)
60  MASS STORAGE IS ":INTERNAL,4,1"
70  ASSIGN @Path1 TO "STRFC"
80  FOR I=1 TO 126
90  ENTER @Path1:Str(I),X2(I),Z(I)
100 NEXT I
110 Fs="DATE ="
120 PRINTER IS 1
130 PRINT "ENTER RUN NUMBER TO WHICH THIS PLOT CORRESPOND (MMDDYY,HHMM)"
140 INPUT Runno
150 GINIT
160 PLOTTER IS 705,"HPGL"
170 !PLOTTER IS CRT,"INTERNAL"
180 GRAPHICS ON
190 CSIZE 2.5,.65
200 MOVE 40,14
210 LABEL "FREE STREAM IS M/S, WITH FILM COOLING "
220 CSIZE 4.5,.65
230 MOVE 40,36
240 LABEL "STANTON NUMBER RATIOS"
250 CSIZE 2.5,.65
260 MOVE 75,83
270 LABEL USING "6A,*,60.40":Fs,Runno
280 CSIZE 3.5,.65
290 MOVE 65,17
300 LABEL "Z (CM) "
310 MOVE 25,45
320 DEG
330 LDIR 90
340 LABEL "S:/Sto"
350 LDIR 0
360 VIEWPORT 30,115,25,93
370 WINDOW -20,20,.3,1.2
380 FRAME
390 AXES S,.1,-20,.30,1,1
400 AXES S,.1,20,1.2,1,1
410 CSIZE 2.0,.65
420 MOVE -17.5,.65
430 LABEL "X (M)"
440 A=.62
450 FOR K=1 TO 6
460 D=A-K*.04
470 Cs(1)="X=1.15"
480 Cs(2)="X=1.25"
490 Cs(3)="X=1.40"
500 Cs(4)="X=1.60"
510 Cs(5)="X=1.80"
520 Cs(6)="X=2.00"
530 MOVE -18,.0
540 LABEL USING "D,8A":K,Cs(K)

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550  PENUP
560  NEXT K
570  CSIZE 1.3,.72
580  FOR J=1 TO 6
590  M=J*21-20
600  FOR I=M TO J*21
610  B(I)=J
620  MOVE Z(I),Str(I)
630  LABEL USING "0":B(I)
640  PENUP
650  NEXT I
660  NEXT J
670  CLIP OFF
680  CSIZE 2.0,.65
690  LORG 2
700  FOR I=.3 TO 1.2 STEP .1
710  MOVE -21.9,I
720  LABEL USING "#,0.0":I
730  NEXT I
740  LORG 5
750  FOR J=-20 TO 20 STEP 5
760  MOVE J,.27
770  LABEL USING "#,000.00":J
780  NEXT J
790  MASS STORAGE IS ":INTERNAL,4"
800  END

```

# APPENDIX D.

## DATA FILES CATALOG

### HEAT TRANSFER DATA DISK No. 1

No	File Name	Date	Inject.	Vortex	Description
001	TDAT1	71787.1702	N	N	15 m/s, baseline
002	IDAT1	"	N	N	"
003	STAV1	"	N	N	baseline $St_{av}$
004	HDAT1	"	N	N	baseline local h
005	TDAT2	72087.1315	N	N	10 m/s base line
006	IDAT2	"	N	N	"
007	STAV2	"	N	N	baseline $St_{av}$
008	HDAT2	"	N	N	baseline local h
009	STRDT2	72187.1524	N	Y	10 m/s $St/St_o$
010	STRV2	"	N	Y	10 m/s $(St/St_o)_{av}$
011	TDAT3	"	N	Y	T(I)
012	IDAT3	"	N	Y	input data
013	TDAT4	72187.1748	N	Y	15 m/s T(I)
014	IDAT4	"	N	Y	input data
015	STRDT1	"	N	Y	$St/St_o$
016	STARV1	"	N	Y	$(St/St_o)_{av}$
017	TDAFC2	72387.1318	Y	N	10 m/s, $M = 0.68$ T(I)
018	IDAFC2	"	Y	N	input data
019	FILDT2	"	Y	N	film cooling data
020	STRFC2	"	Y	N	$St/St_o$
021	STAVFC2	"	Y	N	$(St/St_o)_{av}$

022	TDAFC1	72387.1622	Y	N	15 m/s, T(1)
023	IDAFC1	"	Y	N	Input data
024	FILDT1	"	Y	N	Inj. data
025	STRFC1	"	Y	N	St/Sto
026	STAVFC1	"	Y	N	(St/Sto) <sub>av</sub>
027	TDAFC4	72487.1401	Y	N	10 m/s, repeat
028	IDAFC4	"	Y	N	
029	FILDT4	"	Y	N	
030	STRFC4	"	Y	N	
031	STAVFC4	"	Y	N	
032	TDAFC3	72487.1621	Y	N	15 m/s, repeat
033	IDAFC3	"	Y	N	
034	FILDT3	"	Y	N	
035	STRFC3	"	Y	N	
036	STAVFC3	"	Y	N	
037	TDAFC6	72587.1401	Y	N	10 m/s, M = 1.26
038	IDAFC6	"	Y	N	
039	FILDT6	"	Y	N	
040	STRFC6	"	Y	N	St/Sto
041	STAVFC6	"	Y	N	(St/Sto) <sub>av</sub>
042	TDAFC5	72587.1808	Y	N	15 m/s, M = 0.86
043	IDAFC5	"	Y	N	
044	FILDT5	"	Y	N	
045	STRFC5	"	Y	N	St/Sto
046	STAVFC5	"	Y	N	(St/Sto) <sub>av</sub>
047	TDAFC7	72887.1206	Y	N	15 m/s, M = 0.86
048	IDAFC7	"	Y	N	Repeat
049	FILDT7	"	Y	N	
050	STRFC7	"	Y	N	
051	STAVFC7	"	Y	N	
052	TDAFC8	72887.1353	Y	N	10 m/s, M = 0.68
053	IDAFC8	"	Y	N	Repeat
054	FILDT8	"	Y	N	
055	STRFC8	"	Y	N	St/Sto
056	STAVFC8	"	Y	N	(St/Sto) <sub>av</sub>

057	STAF8	"	Y	N	Stf numbers.
058	TDAFC10	72887.1742	Y	Y	10 m/s, M = 0.68
059	IDAF10	"	Y	Y	Vortex gen. @ 4.70 cm
060	FILDT10	"	Y	Y	"
061	STRFCV10	"	Y	Y	St/Sto
062	STFCV10	"	Y	Y	(St/Sto) <sub>av</sub>
063	TDAFC11	72987.1398	Y	Y	15 m/s, M = 0.47
064	IDAF11	"	Y	Y	Vortex gen. @ 4.70 cm
065	FILDT11	"	Y	Y	"
066	STRFCV11	"	Y	Y	St/Sto
067	STAF11	"	Y	Y	(St/Sto) <sub>av</sub>
068	TDAFC13	72987.1345	Y	Y	15 m/s, M = 0.47
069	IDAF13	"	Y	Y	Vortex gen. @ 3.52 cm
070	FILDT13	"	Y	Y	"
071	STRFCV13	"	Y	Y	"
072	STAF13	"	Y	Y	"
073	TDAFC15	72987.1415	Y	Y	15 m/s, M = 0.47
074	IDAF15	"	Y	Y	Vortex gen. @ 3.00 cm
075	FILDT15	"	Y	Y	"
076	STRFCV15	"	Y	Y	"
077	STAF15	"	Y	Y	"
078	STAF6	72587.1451	Y	N	10 m/s, M=1.26, Stf No
079	STAF7	72887.1206	Y	N	15 m/s, M=0.86, Stf No
080	STAF3	72487.1621	Y	N	15 m/s, M=0.47, Stf No
081	TDAFC21	80187.1354	Y	Y	15 m/s, M = 0.86
082	IDAF21	"	Y	Y	Vortex @ 6.06 cm
083	FILDT21	"	Y	Y	"
084	STRFCV21	"	Y	Y	St/Sto
085	STFCV21	"	Y	Y	averaged St/Sto
086	TDAFC17	80187.1507	Y	Y	15 m/s, M= 0.86
087	IDAF17	"	Y	Y	Vortex @ 4.70 cm
088	FILDT17	"	Y	Y	"
089	STRFCV17	"	Y	Y	"
090	STFC17	"	Y	Y	"

091	TDAFC19	80187.1440	Y	Y	15 m/s. M= 0.86
092	IDAFC19	"	Y	Y	Vortex @ 3.52 cm
093	FILDT19	"	Y	Y	
094	STRFCV19	"	Y	Y	
095	STFCV19	"	Y	Y	
096	TDAFC12	80187.1541	Y	Y	10 m/s. M = 1.26
097	IDAFC12	"	Y	Y	Vortex @ 4.79 cm
098	FILDT12	"	Y	Y	
099	STRFCV12	"	Y	Y	St/Sto
100	STFCV12	"	Y	Y	averaged St/Sto
101	TDAFC14	80487.1321	Y	Y	10 m/s M=1.26
102	IDAFC14	"	Y	Y	Vortex @ 4.79 cm
103	FILDT14	"	Y	Y	
104	STRFCV14	"	Y	Y	
105	STFCV14	"	Y	Y	

## II HEAT TRANSFER DATA DISK #2

No.	FILE NAME	DATE	INJ.	VORTEX	DESCRIPTION
007	STAV2		N	N	10 m/s, St <sub>av</sub> baseline
008	HDATA2		N	N	local h baseline
106	TDAFC16	80487.1412	Y	N	10 m/s, M = 0.98
107	IDAFC16	"	Y	N	no vortex, baseline
108	FILDT16	"	Y	N	for 9 inj. holes F.C.
109	STRFC16	"	Y	N	St/Sto
110	STAF16	"	Y	N	St <sub>f</sub> (I)
111	STAVFC16	"	Y	N	averaged St/Sto
112	TDAFC18	80487.1452	Y	Y	10 m/s, M= 0.98
113	IDAFC18	"	Y	Y	Vortex @ 4.79 cm
114	FILDT18	"	Y	Y	
115	STRFCV18	"	Y	Y	St/Sto
116	STFCV18	"	Y	Y	averaged St/Sto

117	TDAFC20	80487.1529	Y	Y	10 m/s, M=0.98
118	IDAFC20	"	Y	Y	Vortex @ 3.52 cm
119	FILDT20	"	Y	Y	
120	STRFC20	"	Y	Y	
121	STFCV20	"	Y	Y	
122	TDAFC22	80487.1553	Y	Y	10 m/s, M=0.98
123	IDAFC22	"	Y	Y	Vortex @ 6.06 cm
124	FILDT22	"	Y	Y	
125	STRFCV22	"	Y	Y	
126	STFCV22	"	Y	Y	
127	TDAFC24	80987.1943	Y	Y	10 m/s, M=0.98
128	IDAFC24	"	Y	Y	Vortex @ 4.79 cm
129	FILDT24	"	Y	Y	Run for temp. profiles
130	STRFC24	"	Y	Y	St/Sto

### III. TEMPERATURE PROFILES DATA DISK #1

No.	FILE NAME	DESCRIPTION
131	TPRO1	10 m/s, M = 0.98, heated plate, X = 1.867 m
132	TPRO2	Vortex @ 4.79 cm, X = 2.172 m
133	TPRO3	" " " X = 2.48 m
134	TPRO4	10 m/s, M = 0.98, unheated plate, X = 1.867 m
135	TPRO5	Vortex @ 4.79 cm, X = 2.172 m
136	TPRO6	" " " X = 2.48 m
137	TPRO7	" " " X = 1.48 m
138	TPRO8	10 m/s, M=0.98, heated plate, X=1.48 m, Vt. @ 4.79 cm
139	TPRO9	10m/s, M=.98, unheated plate, X=1.48 m, V @ 3.52 cm
140	TPRO10	" " " V @ 6.06 cm
141	TPRO11	10 m/s, M=1.26, unheated plt., X=1.48 m, V @ 4.79 cm
142	TPRO12	10 m/s, M= 0.98, unheated plate, No vortex, X=1.48 m



#### IV. TEMPERATURE PROFILES DATA DISK #2

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143	TPRO13	10 m/s. boundary layer with film cooling. $M = 0.98$
144	TPRO14	10 m/s. boundary layer heated plate only.

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145	PPEOF	10 m/s. $M = 1.26$ . $V_\infty = 4.79$ cm. Pressure probe profile
146	CAL	data, at $X = 1.48$ m
147	VELPRO	velocity profiles
148	PLOTVOR	vorticity profiles

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